Japanese Technology Evaluation Center

JTEC

JTEC Panel Report on

Advanced Manufacturing Technology for Polymer Composite Structures In Japan

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April 1994

International Technology Research Institute
JTEC / WTEC Program
Loyola College
Baltimore, Maryland 21210-2699

JTEC PANEL ON ADVANCED MANUFACTURING TECHNOLOGY FOR POLYMER COMPOSITE STRUCTURES

Sponsored by the National Science Foundation, the Department of Energy, the Army Research Office and the Air Force Office of Scientific Research of the United States Government

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INTERNATIONAL TECHNOLOGY RESEARCH INSTITUTE JTEC/WTEC PROGRAM

The Japanese Technology Evaluation Center (JTEC) and its companion World Technology Evaluation Center (WTEC) at Loyola College provide assessments of foreign research and development in selected technologies under a cooperative agreement with the National Science Foundation (NSF). Loyola's International Technology Research Institute (ITRI), R.D. Shelton Director, is the umbrella organization for JTEC, WTEC, and TTEC (the Transportation Technology Evaluation Center, funded by the Federal Highway Administration). Paul Herer, Senior Advisor for Planning and Technology Evaluation at NSF's Engineering Directorate, is NSF Program Director for JTEC and WTEC. Other U.S. government agencies that provide support for the program include the National Aeronautics and Space Administration, the Department of Energy, the Department of Commerce, and the Department of Defense.

JTEC/WTEC's mission is to inform U.S. policy makers, strategic planners, and managers of the state of selected technologies in foreign countries in comparison to the United States. JTEC/WTEC assessments cover basic research, advanced development, and applications/commercialization. Small panels of about six technical experts conduct JTEC/WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in universities and in industry/government labs.

The ITRI staff at Loyola College help select topics, recruit expert panelists, arrange study visits to foreign laboratories, organize workshop presentations, and finally, edit and disseminate the final reports.

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LOYOLA COLLEGE IN MARYLAND

International Technology Research Institute

Japanese Technology Evaluation Center
June 20, 1994

Dear Colleague:

I am happy to transmit to you the *JTEC Panel Report on **Advanced Manufacturing Technology for Polymer Composite Structures in Japan***. To gain material for this report, the six panel members conducted on-site visits to 21 different locations in Japan -- research labs, industrial facilities, and government agencies. The report covers applications for aerospace, civil construction, automobile manufacturing, and other industries. The panel concluded that the same basic manufacturing technologies are practiced in the United States and Japan. However the panel observed a very great emphasis on maintaining quality in Japan and impressive efforts to reduce composite part count and otherwise gain efficiencies in manufacturing.

I would like to thank the sponsors of this report: Paul Herer and Bruce Kramer of the National Science Foundation; Andrew Crowsen, Army Research Office; Charles Lee, Air Force Office of Scientific Research; George Jordy, Don Freeburn, and Paul Maupin, Office of Energy Research. Of course we are greatly indebted to the productive leadership of our panel chair Dick Wilkins and to the high level of energy and excellence of all the panelists. We also wish to thank our gracious hosts from the institutions that were visited in Japan.

More JTEC and World Technology Evaluations Center (WTEC) studies will be available this summer -- ***Advanced Electronics Displays in Russia, Belarus, and Ukraine; Research Submersibles and Undersea Technologies in Europe, Russia and Ukraine; Micro-electromechanical Systems (MEMS) in Japan; and Electronic Packaging in Japan***. A new JTEC study on optoelectronics has just begun.

If your are interested in receiving reports on any of these topics, please notify us by phone, fax, or e-mail. If you know of someone who needs the enclosed report, we will be happy to oblige until are stocks are exhausted. Older reports may be obtained from NTIS as discussed on the inside back cover.

Please assist us by completing the survey form that you find with the report. Thank you for your interest and support.

Sincerely,

Michael J. DeHaemer

Michael J. DeHaemer
Director

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Polymer Composites in Japan - June 1994

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JTEC Panel on

ADVANCED MANUFACTURING TECHNOLOGY FOR POLYMER COMPOSITE STRUCTURES IN JAPAN

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FINAL REPORT

April 1994

This document was sponsored by the National Science Foundation (NSF), the Department of Energy, the Army Research Office, and the Air Force Office of Scientific Research under NSF Grant ENG-9111333, awarded to the International Technology Research Institute (JTEC/WTEC Program) at Loyola College in Maryland. The Government has certain rights in this material. The views expressed herein are solely those of the authors and do not necessarily reflect those of the United States Government, the authors' parent institutions, or Loyola College.

ABSTRACT

This report covers Japanese research and development in the manufacturing of polymer composite structures. The study was supported by the National Science Foundation, the Department of Energy, the Army Research Office, and the Air Force Office of Scientific Research. Manufacturing technologies covered include lamination, pultrusion, filament winding, compression molding, thermoforming, and liquid molding (RTM, SRIM, etc.). Applications covered include aerospace (civil and military), civil engineering, automotive, and industrial. In addition, the report covers developments in composite materials, manufacturing and processing science, and composite product and process development methods. The report is based on site visits in Japan conducted in the fall of 1992, with updates provided by the panel's Japanese hosts in 1993 and early 1994. The panel concluded that the same basic manufacturing technologies are practiced in both the United States and Japan. However, Japanese companies implement these technologies with greater respect for detail, leading directly to the high quality evident in their operations and parts, also reducing errors and costs. The panel observed impressive Japanese efforts to reduce composite detail part count, a high level of excellence in co-curing, and an emphasis on dry-fiber preforming.

JTEC/WTEC

Michael J. DeHaemer, Principal Investigator, JTEC/WTEC Director
Geoffrey M. Holdridge, JTEC/WTEC Staff Director and Series Editor
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Advance Work in Japan performed by Alan Engel of ISTA, Inc.

International Technology Research Institute at Loyola College

R. D. Shelton, Director

 The ISBN number for this report is 1-883712-32-7. This report is distributed by the National Technical Information Service (NTIS) of the U.S. Department of Commerce as NTIS Report # PB94-161403. Information on ordering from NTIS and a list of JTEC/WTEC reports available from NTIS is included in the inside back cover of this report.

FOREWORD

The National Science Foundation has been involved in funding technology assessments comparing the United States and foreign countries since 1983. A sizable proportion of this activity has been in the Japanese Technology Evaluation Center (JTEC) and World Technology Evaluation Center (WTEC) programs. We have supported more than 30 JTEC and WTEC studies over a wide range of technical topics.

As U.S. technological leadership is challenged in areas of previous dominance, such as aeronautics, space, and nuclear power, many governmental and private organizations seek to set policies that will help maintain U.S. strengths. To do this effectively requires an understanding of the relative position of the United States and its competitors. The purpose of the JTEC/WTEC program is to assess research and development efforts ongoing in other countries in specific areas of technology, to compare these efforts and their results to U.S. research in the same areas, and to identify opportunities for international collaboration in pre-competitive research.

Many U.S. organizations support substantial data gathering and analysis efforts directed at nations such as Japan. But often the results of these studies are not widely available. At the same time, government and privately sponsored studies that are in the public domain tend to be "input" studies. That is, they provide enumeration of inputs to the research and development process, such as monetary expenditures, personnel data, and facilities, but do not provide an assessment of the quality or quantity of the outputs obtained.

Studies of the outputs of the research and development process are more difficult to perform because they require a subjective analysis performed by individuals who are experts in the relevant technical fields. The National Science Foundation staff includes professionals with expertise in a wide range of disciplines. These individuals provide the technical expertise needed to assemble panels of experts that can perform competent, unbiased, technical reviews of research and development activities.

Specific technologies, such as telecommunications, biotechnology, and nuclear power, are selected for study by government agencies that have an interest in obtaining the results of an assessment and are able to contribute to its funding. A typical assessment is sponsored by two to four agencies. In the first few years of the program, most of the studies focused on Japan, reflecting concern over Japan's growing economic prowess. Studies were largely defined by a few federal mission agencies that contributed most of the funding, such as the Department of Commerce, the Department of Defense, and the Department of Energy.

The early JTEC methodology involved assembling a team of U.S. experts (usually six people, from universities, industry, and government), reviewing the extant literature, and writing a final report. Within a few years, the program began to evolve. First, we added site visits. Panels traveled to Japan for a week visiting 20-30 industrial and research sites. Then, as interest in Japan increased, a larger number of agencies became involved as co-sponsors of studies. Over the 10 year history of the program, 15 separate branches in six agencies of the Federal Government (including NSF) have supported JTEC and WTEC studies.

Beginning in 1990, we began to broaden the geographic focus of the studies. As interest in the European Community (now the European Union) grew, we added Europe as an area of study. With the breakup of the former Soviet Union, we began organizing visits to previously restricted research sites opening up there. These most recent WTEC studies have focused on identifying opportunities for cooperation with researchers and institutes in Russia, Ukraine, and Belarus, rather than on assessing them from a competitive viewpoint.

In the past four years, we have also begun to considerably expand dissemination efforts. Attendance at JTEC/WTEC workshops (in which panels present preliminary findings) increased, especially industry participation. Representatives of U.S. industry now routinely number 50% or more of total attendance, with a broad cross section of government and academic representatives making up the remainder. JTEC and WTEC studies have also started to generate increased interest beyond the science and technology community, with more workshop participation by policymakers and better exposure in the general press (e.g., *Wall Street Journal*, *New York Times*). Publications by JTEC and WTEC panel members based on our studies have increased, as has the number of presentations by panelists at professional society meetings.

The JTEC/WTEC program will continue to evolve in response to changing conditions in the years to come. We are now considering new initiatives aimed at the following objectives:

- Expanded opportunities for the larger science and technology community to help define and organize studies. This may be accomplished through a proposal competition in which NSF would invite universities and industry (preferably working together) to submit proposals for JTEC and WTEC studies. These would then be peer reviewed much as NSF reviews research proposals.

- Increased industry sponsorship of JTEC and WTEC studies. For example, NSF recently funded a team organized by the Polymer Science & Engineering Department at the University of Massachusetts (Amherst) to visit Japan for two weeks studying biodegradable plastics and polymers R&D there. Twelve industrial firms put up over half of the funds.

- Including a broader policy and economic context to our studies. This is directed at the need to answer the question, "So what?" that is often raised in connection with the purely technical conclusions of many JTEC and WTEC panels. What are the implications of the technical results for U.S. industry and the economy in general? We will be adding an economist to an upcoming JTEC study on optoelectronics in Japan as a new effort to address these broader questions.

In the end, all government funded programs must answer the following question: *How has the program benefitted the nation?* I would like to point out a few of the benefits of the JTEC/WTEC program:

- JTEC studies have contributed significantly to U.S. benchmarking of the growing prowess of Japan's technological enterprise. Some have estimated that JTEC has been responsible for over half of the major Japanese technology benchmarking studies conducted in the United States in the past decade. Our reports have also been widely cited in various competitiveness studies.

- These studies have provided important input to policymakers in federal mission agencies. JTEC and WTEC panel chairs have given special briefings to senior officials of the Department of Energy, the NASA Administrator, and even the President's Science Advisor.

- JTEC/WTEC studies have been of keen interest to U.S. industry, providing managers with a sense of the competitive environment internationally. Members of the recently completed study on satellite communications have been involved in preliminary discussions concerning the establishment of two separate industry/university consortia aimed at correcting the technological imbalances identified by the panel in its report.

- JTEC and WTEC studies also have been valuable sources of information for both U.S. and foreign researchers, suggesting potential new research topics and approaches, as well as opportunities for international cooperation. One JTEC panelist was recently told by his Japanese hosts that, as a result of his observations and suggestions, they have made significant new advances in their research.

- Not the least important is the educational benefit of the studies. Since 1983 over 170 scientists and engineers from all walks of life have participated as panelists in the studies. As result of their experiences, many have changed their viewpoints on the significance and originality of foreign research. Some have also developed lasting relationships and ongoing exchanges of information with their foreign hosts as a result of their participation in these studies.

As we seek to refine the JTEC/WTEC program in the coming years, improving the methodology and enhancing the impact, we will still be operating from the same basic premise that has been behind the program from its inception: the United States can benefit from a better understanding of cutting-edge research that is being conducted outside its borders. Improved awareness of international developments can significantly enhance the scope and effectiveness of international collaboration and thus benefit all of our international partners in collaborative research and development efforts.

Paul J. Herer
National Science Foundation
Arlington, VA

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EXECUTIVE SUMMARY

INTRODUCTION

The United States has invested a great deal of effort in developing polymer composite structures. Now, the government seeks expanded applications. Experts perceive that the barrier to expanded applications is the high cost of manufacturing. This is not only an American issue, but an international one. Consequently, the government asked this panel to evaluate the status and outlook for manufacturing, or fabrication, technology in the U.S. and Japan, with an eye toward finding or developing mechanisms of cooperation.

The title for this study, "Advanced Manufacturing Technology for Polymer Composite Structures," reflects the panel's emphasis on polymer composites, and the focus on manufacturing technology as the key to wider use of composites by lowering the cost of using them.

For the purpose of this study, we define a composite as a combination of two or more materials that enhances their properties. Composites are being used because of their superior capabilities in the following categories:

- Stiffness/weight
- Ability to tailor structural performance
- Ability to tailor thermal expansion
- Strength/weight
- Corrosion resistance
- Fatigue resistance

Familiar applications include boats, surf boards, fishing rods, racquets, skis, and tool handles. Many advanced applications of composites have been made in the aircraft industry:

- Commercial aircraft flaps, slats, elevators, tails
- Helicopter blades and bodies
- F-16 tail surfaces
- F-18 wings and tails
- AV-8B Harrier fuselage, wings, tails
- F-117
- B-2

The manufacturing methods of major interest for this study are shown in Table E.1.

Table E.1
Manufacturing Methods of Major Interest

Lamination	Hand or machine layup of dry pre-impregnated layers; vacuum bag, press, or autoclave molding
Pultrusion	Continuous pulling of fiber preform through resin bath and heated die
Filament Winding	Dry or wet winding around mandrels
Compression Molding	Press molding of structural molding compound (SMC)
Thermoforming	Stamping of pre-impregnated fibers and resin
Liquid Molding (RTM, SRIM, etc.)	Injection of resin into mold containing fiber preform

APPROACH

The panel's approach was to develop a draft report summarizing the status and outlook for advanced manufacturing technology of polymer composite structures in the U.S. This report was given to the hosts in the approximately 20 Japanese organizations that the 10-person JTEC team visited over a 10-day period in December 1992.

Sponsors for this study were:

NSF: Paul Herer
Army Research Office: Dr. Andrew Crowson
Air Force Office of Scientific Research: Dr. Charles Lee
Department of Energy: Dr. Paul Maupin, Dr. George Jordy

The study was carried out under the auspices of the Japanese Technology Evaluation Center (JTEC) at Loyola College, funded by the above agencies through NSF's grant to JTEC. JTEC studies are carried out by the International Technology Research Institute (ITRI) at Loyola College; ITRI is directed by Dr. R.D. Shelton. Within ITRI, the JTEC Principal Investigator and Director is Dr. Michael J. DeHaemer and the JTEC/WTEC Staff Director and Series Editor is Geoff Holdridge.

As detailed in Appendix B, the panel had unique qualifications for this study:

Dick Wilkins (Chair), University of Delaware

17 years at General Dynamics, Fort Worth in composites development (Coordinator of F-16 Tail Certification)

Five years as Director of UD Center for Composite Materials (two years as President of American Society for Composites)

Two years as Director of Institute for Applied Composites Technology

Moto Ashizawa, Ashizawa and Associates Composites Engineering

15 years in composites design, analysis and development at Douglas

10 years in composites program management, certification, and manufacturing at Douglas

One year in composites consulting in both the U.S. and Japan

Jon DeVault, Advanced Research Projects Agency (ARPA)

25 years experience in advanced materials industry with Hercules

Former President of Hercules Advanced Materials & Structures Company

Now starting a new position organizing composites initiatives at ARPA

Dee R. Gill, McDonnell Douglas

25 years in manufacturing methods development at Hercules

Four years as Director of Production Operations and Director of Manufacturing in the New Aircraft Division of McDonnell Douglas

Vistasp Karbhari, Center for Composite Materials

Scientist, Center for Composite Materials, U. of Delaware

Research Assistant Professor in Civil Engineering, U. of Delaware

Joe McDermott, Composites Services Corp.

11 years as Director, Composites Institute of SPI

12 years in composites consulting in both the U.S. and Japan

During the visit to Japan, the panel was assisted by a number of highly qualified sponsor representatives:

Dr. Iqbal Ahmad, ARO

Excellent background in materials science

Army Representative in Japan

Dr. Alan Engel, ISTA, Inc.

Several years in polymer and composites research at DuPont

JTEC contractor for advance arrangements in Japan

Dana Granville, ARL

Army Materials Directorate Coordinator for Composites

Dr. Bruce Kramer, NSF
Program Director for Manufacturing & Materials Processing

Xavier Spiegel, JTEC
Teaches materials at Loyola College

Our special thanks go to Dr. Tsuyoshi Hayashi, Professor Emeritus at the University of Tokyo, for his gracious help in organizing our study.

The mission of the study was to summarize the current status and future outlook of polymer composite structures in Japan and in the United States. It was motivated by the desire of the U.S. to move from invention to commercialization, which dictates advancements for low cost, repeatable manufacturing. The hope was expressed to the Japanese hosts that the U.S. and Japan could cooperate so as to expand the market for composites.

Available literature was used to summarize the U.S. status in a document for the Japanese hosts to see the scope being sought. Available literature and key Japan site visits were also used to summarize the Japanese status. Summary findings were presented at a Workshop in Washington, D.C. on February 18, 1993. This report was then developed.

OVERALL FINDINGS

It is overwhelmingly clear that individual organizations in both Japan and the United States practice the same basic manufacturing technologies. But Japanese companies practice them with a much greater respect for detail. This respect for detail leads directly to the high quality evident in their operations and parts.

The Japanese hosts expressed great confidence in the training and skills of their work force. At the same time, factory workers help develop the fabrication methods to achieve the best chance of success.

Many of the processes observed were relentlessly developed to remove chances for errors and reduce cost. This persistence was striking.

The panel observed impressive efforts to reduce composite detail part count. One derivative is the high level of excellence achieved in co-curing. Another is the observed emphasis on dry-fiber preforming.

There were a number of interesting areas showing strong potential for success. These included:

Co-cured Omega stringer panels
3-D and 2.5-D weaving
Curved pultrusion
Super composite bolt
Continuous forming of thin-walled pipes

DETAILED FINDINGS

The JTEC panel's qualitative comparisons between the United States and Japan in advanced manufacturing technology for polymer composite structures are shown in Table E.2. The remainder of the report addresses each of the topics listed in the table in some detail. Conclusions in each of these topics are also summarized below.

Aerospace

The aerospace sector is focused on commercial applications of aerospace technology. Japanese technology was introduced through alliances with U.S. and European companies, from which the Japanese companies have transferred both good and bad habits.

Automotive and Industrial

While the U.S. seems to still have opportunities in automotive applications, Japan appears to be stymied by recycling concerns.

Japan is quite aggressive in this industrial field. Many cost-driven applications are being tried.

Civil Engineering

In contrast to the U.S., where the construction industry is fragmented, the Japanese opportunities in civil engineering applications are many and varied.

Materials

There is still a large effort to introduce pitch carbon fiber into applications. The economics are still mysterious, however.

Emphasis on thermoplastics was evident, in spite of the reduction in emphasis in the U.S. Similarly, high temperature resins are getting much attention.

TABLE E.2
Japan Compared to U.S. in Advanced Manufacturing Technology for Polymer Composite Structures
(See Key below)

	R & D		PRODUCTION	
	Status	**Trend**	**Status**	**Trend**
AEROSPACE	–	=	–	–>
Advanced Materials				
Carbon Fiber (Pan)	0	=	0	=
Carbon Fiber (Pitch)	+	–>	+	–>
Thermoset Resin	0	=	0	–>
Thermoplastic Resin	–	–>		
Processes				
Hand Layup	0	=	0	–>
Auto. Tape Layup	0	=	0	–>
Ply Cutting & Stacking	–	–>	–	–>
Filament Winding	–	=	–	=
Tow Placement	–	<–	–	<–
Pultrusion	0	–>	0	–>
RTM	0	–>	0	=
Thermoforming	–	<–		
Co-Curing	+	–>	+	–>
Tooling	+	–>	+	–>
SPORTING GOODS	0	=	0	=
AUTOMOTIVE	–	<–	–	<–
INDUSTRIAL	–	<–	–	<–
CIVIL ENGINEERING	+	–>	+	–>

Key:

+	Japan ahead of U.S.	–>	Japan gaining ground
0	Japan even with U.S.	=	Japan holding position
–	Japan behind U.S.	<–	Japan losing ground

Manufacturing/Processing Science

In contrast to the U.S. approach of developing computational models to understand processes better, Japanese manufacturing science appears to reside in experienced workers who develop understanding of the processes over long periods of time.

Product and Process Development Methods

Japanese product and process development methods use concurrent engineering by definition. Japanese teams have developed the human factors issues far beyond those in the West.

POLICY CONSIDERATIONS

Advantages in Japan

- The Japanese appear to be able to accomplish more with less.
- They drive to low cost from a life cycle viewpoint.
- Manufacturing people have high status.
- While the U.S. is better at university-industry links and university education, Japan is better at *keiretsu*, consortia, and industry-government links. A good example is the 3-D Composites Research Corporation that was formed by a number of Japanese organizations for a fixed number of years to advance the technology of preforming.
- The Japanese will derive a cost advantage from government projects in standards and data bases.
- The Japanese appear to be better at a number of aspects of composites manufacturing. They focus more on long-range strategy, and invest more up front to ensure success. These up-front investments are frequently justified by careful cost trade-offs. The other critical investment is in the training of the entire work force to achieve a unified approach throughout the company. The high-quality people assigned to production management maintain a high priority on manufacturing. They enforce high standards and goals in development and execution of fabrication processes. The above-mentioned attention to detail is a direct result.

IMPRESSIONS

Japan and the U.S. have much to gain from each other. Each country has different strengths to bring to composites manufacturing. Many of our hosts expressed the belief that they must develop ways to cooperate with the U.S. In perspective, producers in both countries can reduce costs by obtaining a deeper understanding of basic processes. Companies in both countries must also develop a unified basis for understanding what it takes to make repeatable composite structures so that new markets may be opened with more confidence and reliability. It is also clear that the process advancements made by the Japanese can be transferred to the U.S. only by also transferring the spirit of cooperation that exists within Japanese companies.

CHAPTER 1

MANUFACTURING TECHNOLOGY FOR POLYMER COMPOSITE STRUCTURES

Moto Ashizawa
Dee R. Gill

INTRODUCTION

This chapter covers the manufacturing technologies used by U.S. and Japanese aerospace companies in the fabrication of aerospace products made from polymer composites. This discussion of composites manufacturing technologies is presented in the context of the aerospace industry because the aerospace industry has been and remains at the cutting edge of this technology. The emphasis will be on the methods used to reduce the per-pound cost of finished composite structures. The chapter begins with a brief discussion of the history of composites manufacturing, particularly in the aerospace sector. The remainder of the chapter is a detailed and comparative discussion of the current status of relevant composites manufacturing technologies in the U.S. and Japan, followed by discussion of possible future trends in the technology, particularly for demanding advanced aerospace applications.

BRIEF HISTORY OF EVOLUTION IN COMPOSITES MANUFACTURING TECHNOLOGY

The introduction of boron filaments in the early 1960s lead to the birth of advanced composites technology. High modulus, high strength continuous filaments, like boron and later carbon, have profoundly impacted today's aerospace airframe design and manufacturing. The application of boron/epoxy composites and the

development of their manufacturing technology were limited by several factors: (1) the high cost of boron filament and no prospects for replacing expensive tungsten substrate, (2) the limitation on a bend radius of no less than 1", (3) the high cost of diamond tools required for machining, drilling, and trimming, (4) the fact that the applications were limited to one form of prepregs (i.e., they were only available in 3" wide tape). Below is a summary of manufacturing techniques for boron/epoxy.

- Most, if not all, were done by labor intensive hand layup on flat and moderately curved metal tools, using 3" wide tape (fabrics not available).

- Extremely simple tools were used because of the bend radius limitation.

- Hand-held tools with diamond tips and cutting edges were used for drilling and trimming. Existing machines were used with diamond cutters for machining.

- Crude automated tape layup (ATL) machines for 3" tape were available for R&D, but no production versions were developed.

Carbon and aramid fibers and prepregs were introduced in the latter 1960s. These fibers have some distinct advantages over boron: (1) their extremely small diameter (6 to 10 microns) reduced the bend radius to less than 1/16", (2) traditional high-strength steel could be used instead of diamond-tip tools for cutting, trimming, drilling, and machining, (3) there was a greater potential for achieving low cost ($10/lb compared to $90/lb for boron in 1960s dollars), (4) they were available in a variety of strengths, stiffnesses, and other mechanical properties. The introduction of carbon fibers drastically increased the variety of applications and changed the way airframe structures were manufactured. Below is a list of manufacturing techniques and aids developed for carbon composites:

- Many different kinds of fabrics and widths (some up to 60" wide) substantially increased the speed of hand layup processes. Drapeability was enormously helpful in the manufacturing of complex and concave products.

- Tapes started to appear in 3, 6, 12, and 24 inch widths, which resulted in increased layup speeds.

- Computer-controlled sophisticated ATLs began to appear in production. Improvements continue to this date. ATL can take different tape widths, and alignment becomes nearly perfect.

- ACM (automatic cutting machines) flooded the market. These included the Gerber Cutter, ultrasonic, laser, and water jet machines. Improvements continue to this date.

- o The one-shot co-cured techniques using expandable mandrels became popular. Several different kinds of washable mandrels were also introduced. Some large structural boxes were made this way.
- o Non-metallic (especially graphite or carbon) tools also became popular.
- o Filament winding and braiding became possible with carbon and aramid fibers.
- o Sophisticated multi-angled ply orientation pultrusion machines appeared.
- o Research and development yielded tow placement, RTM (resin transfer molding), injection molding, and other new manufacturing technologies.
- o Compression molding, diaphragm forming, hydroforming, magneforming, deepdrawing, stamping, etc., began to appear in abundance.
- o Preforms and stitched preplies appeared
- o 3-D and multi-directional weaving were used for improved damage tolerance and as potential replacements for joints and fittings.

Thanks to the introduction and continuous improvements in carbon fiber and prepreg technology, a quantum jump in progress was observed in advanced materials technology in general, and in manufacturing technology in particular. It is expected that advanced composites technology will continue to expand and improve. However, the rate and direction of expansion and improvement may be quite different than what has been observed in the past. The primary reason for this difference is the change in the driving forces of recent years.

When advanced composites technology was first introduced in the early 1960s, the emphasis was on increased performance by means of reducing structural weight; very little attention was given to low-cost manufacturing. The demand for high performance (reduced weight) was further aggrandized by the high cost of fuel which resulted from the oil shocks of 1973 and 1979. The well known ACEE (Aircraft Energy Efficiency) program in the United States emerged from the fear of substantial increases in future fuel costs. The slogan was "reduced weight for reduced fuel cost." To achieve high performance, some designs called for individually tailor-made plies which saved a mere ounce at a substantial cost penalty. Instead of the cost of fuel increasing as predicted, it has actually dropped considerably (in real dollars) since the early 1980s, and the demand for high performance has somewhat diminished. Consequently, the ACEE program has lost much of its funding and clout.

The advanced composites industry has begun to recognize that the potential market for composites in commercial transport applications is much greater than that in military aircraft applications due to the sheer size of commercial transport and its large production runs and rates. This has caused the shift from military to commercial applications to accelerate in recent years.

The historical development of the Japanese composites manufacturing technology in the aerospace industry dates back to the early 1970s, and follows closely that of the United States. Figures 1.1 and 1.2 give a quick review of past and present programs at Mitsubishi and Kawasaki Heavy Industries. As can be seen in the charts, from 1970 to 1982 the composites work was largely internally sponsored. The Japanese focus from the beginning was on primary structures. The bulk of the subcontract work done in Japan for Boeing and Douglas during the 1980s was on control surfaces and fairings. Despite the wishes of the Japanese to design and build composite primary structures for the Boeing 777, the Japanese aircraft consortium instead received a contract for metallic primary structures from Boeing.

Although numerous composite activities have taken place in the Japanese aerospace industry, the magnitude of those activities has been quite small when compared to that of the United States, as depicted in Table 1.1.

Table 1.1
Carbon Fiber Usage in 1989
(tons)

APPLICATION	USA	JAPAN	EUROPE	ASIA
AEROSPACE	1150	40	530	0
SPORTING	400	720	270	1080
INDUSTRIAL & OTHERS	550	350	300	10

It is evident from Table 1.1 and Table 1.2 that Japan's emphasis has been more on sporting goods and carbon fiber production than on aerospace. It is interesting to note that in Japan it was the textile industry (the world leader in the late 1950s and 1960s) which began the development and production of carbon fibers, whereas in the U.S. it was the chemical industry which took the initiative.

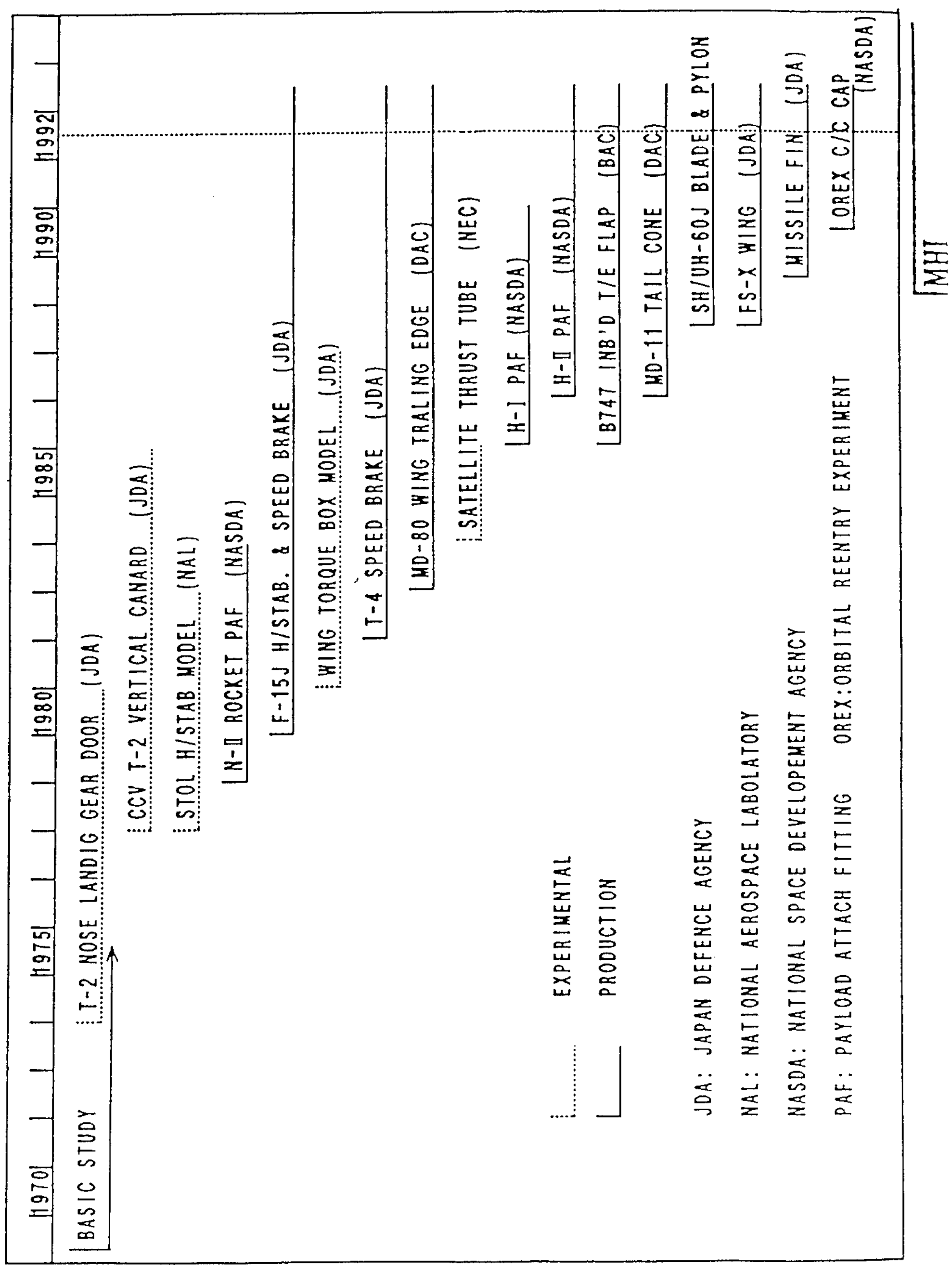


Figure 1.1. Major Composites Applications of MHI

No.	Products		1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	Material and Remark
①	P2V-7 & P2J Radome	1959																GFRP/Glass Honeycomb First composite part
②	C-1 Ground Spoiler	1974																CFRP/Al Honeycomb First CFRP part (Flight evaluation test conducted)
③	B747SP Flap	1975																GFRP/Glass Honeycomb Co-cure molding process
④	BK117 Doors & Panels																	AFRP/Nomex Honeycomb ; Co-cure molding process, water jet cutting
⑤	P-3C Radome & Mad Boom																	GFRP/Glass Honeycomb Fabrication technique of large radome
⑥	F-15 Vertical Fin Torque Box & Rudder																	BFRP/Al Honeycomb NDI technique with ultrasonic facilities
⑦	T-4 Aileron, Rudder & Nose LDG Door																	CFRP/Nomex Honeycomb AFRP/Nomex Honeycomb
⑧	MD-80 Flap Hinge Fairing																	AFRP Laminate CFRP molding tool
⑨	B747 Outboard Flap																	CFRP/Nomex Honeycomb Molding process of long parts
⑩	CH-47 Transmission Oilpan																	AFRP Laminate ; Molding Process of Compicated parts and laser triming
⑪	FSX Fuselage Cover Panels & Main LDG Door											under development						CFRP Laminate (Co-cured), CFRP/Al Honeycomb Medium modulus, tough resin comp.
⑫	C-1 STOL Flap Trailing Edge																	GFRP/Glass Honeycomb Bismaleimide resin comp.

AFRP : Kevlar fiber reinforced plastic
BFRP : Boron fiber reinforced plastic
CFRP : Carbon fiber reinforced plastic
GFRP : Glass fiber reinforced plastic

Figure 1.2. Composite Products of Kawasaki Heavy Industries

Table 1.2
Carbon Fiber Production Capability in 1991 (Pan & Pitch)
(tons)

USA	JAPAN	EUROPE	ASIA
4560	6870	1150	250

CURRENT COMPOSITES MANUFACTURING TECHNOLOGY

There is a general notion and confidence among the composites community that high-performance all-composite aircraft can be designed and built using currently available manufacturing technology if cost and schedule restrictions are ignored. The proof can be seen in such aircraft as F-117, B-2, Starship, AVTEK 400, and Voyager.

Furthermore, composites have already proven their worth as weight-saving materials. Therefore, the current challenge is not to make lighter-weight all-composite aircraft (a dream airplane several years ago), but to make composite components economically attractive. The effort to produce economically attractive composite components has resulted in several innovative manufacturing techniques currently being used in the composites industry. It is obvious, especially for composites, that improvement in manufacturing technology alone is not enough to overcome the cost hurdle. It is essential that there be an integrated effort of design, material, process, tooling, quality assurance, manufacturing, and even program management for composites to become competitive with metals.

Table 1.3 shows current composites technology with cost reduction as a driving force.[1] Table 1.3, although not complete, provides a good idea of where composites technology stands today. Even with this impressive list of composites technologies, it is still not possible for composites to compete economically with metals. Nevertheless, for certain applications, the use of composites rather than metals has in fact resulted in both lower cost and less weight. Some examples are cascades for engines, most of the compound curved fairings and fillets, replacements for welded metallic parts, cylinders, tubes, ducts, blade containment bands, and many more.

[1] Although this study focuses on manufacturing technology, the importance of other areas to achieving overall cost reduction cannot be ignored because they directly and indirectly affect manufacturing technology.

Table 1.3 includes technologies with real potential for cost reduction, and those that are current and past composites "buzz words." In the U.S. it is often said that, "the best thing heard about a new material or process is the *first* thing heard." This is a sad testimonial on our propensity for overstatement.

TECHNOLOGIES

The following is a review of some of the most important composites manufacturing technologies, including a discussion in each case of the current state-of-the art in the United States and Japan and the relevant research issues.

Spray Layup

Spray layup has very little application in aerospace. This technology produces low specific strength structures which usually do not belong on the end product. Spray layup is being used to join back-up structures to composite face sheets on composite tools. Spray layup is also in limited use for obtaining fiberglass splash from transfer tools.

The JTEC team did not observe spray layup equipment in Japan, nor was evidence of its use seen in any of the tooling. The large bond jigs used for Boeing and Douglas parts are usually dictated by customer tooling handbook designs. This may stifle some innovation. Handbooks help avoid "reinvention of the wheel," but can promote "not invented here" problems.

Hand Layup

Hand layup is the most common method of producing composites parts in the U.S. aircraft industry. At McDonnell Aircraft, 100% of the aircraft composites are produced by hand layup. An area which relates to this and which is covered in a later section is ply cutting and stacking.

The primary methods of automation in hand layup relate to computer software. Each ply has a separately identified part number.

Software is used to generate flat patterns from the layer surface and the ply boundary. Software is also used to find the most efficient nest of cut plies to minimize the scrap. Gerber-type textile nesting programs are used. Many different types of parts are laid up, and plies are often spoiled during handling. This usually means a different mix of parts are nested each day. Unidirectional parts may be broken up into two or three subparts to make a better fitting nest. The cut parts are usually hand sorted into ply packs and packaged.

Table 1.3
Composites Technology with Cost Reduction as Driving Force

Concurrent engineering (or IPD)	Paperless design & factory
Simple is beautiful (design philosophy)	Automatic FEA modeling
Automated optimization	Menu driven design
3-D CAD/CAM	Analysis base certification
Low cost fibers and fabrics	Commonality in design
Large tow (12K instead of 3K)	Pre-plying
Reduced cure time	Preforming
Large ply drop-offs	Highly drapeable fabric
Electro-deposited Nickel tools	Cast-to-size tooling
Invar for tools	Graphite tools
Co-curing (eliminate joints)	Blind fastener for composites
Wash-out mandrels	Oven cure
Computer controlled autoclave	Night time curing
Integrally-heated tooling	Inflatable mandrels
High speed machining	Mechatronics in tooling
Integrated assembly/QC tools	Automatic assembling
Automatic tape-layup machine	Automatic cutting machine
Computer aided nesting	Braiding
Automated bonding	Automatic tow placement
Radiation curing	Microwave curing
Pultrusion	Continuous sandwich panel
Resin transfer molding	3-D weaving
Foam core	Fly away tools
Automated QC systems	SPC
Reusable silicon vacuum bag	Stamping
Hot press	Diaphragm
User friendly PC analysis codes	Reduced computing time and cost
Filament winding consolidation	
Laser cured hot roll	

The material to be laid up is delivered to the layup cell at the start of the shift. Most large layup facilities use electronic work orders and work instruction. Bar code is widely used for worker identification and part identification.

Plies are located on the tool in various ways. The most common is within the instruction set, in the form of a sketch or a verbal description. Mylar templates are

used for large parts and with multiple, closely spaced ply boundaries. Mylars are generated with the same software that generates the digital data for ply cutting.

As in the U.S., hand layup is used extensively in Japan. The Japanese are not as automated on the shop floor. The U.S. is working toward a paperless system. The resolve to eliminate paper was not evident in Japan. There are not large numbers of CRTs in the manufacturing areas. Textile type pattern cutters do not, extensively, use bar code labelers. Plies are located by template or layout. The work force is so well trained that automation is not needed to ensure quality. If it does not pay off well, the Japanese will not pursue it.

Research in this area is directly improving the methods of locating the ply on the tool. The laser projector system is in limited use. It traces ply boundary, ply identification, and ply orientation information on the tool or composite surface. The system has contour limitations and requires high projection heights for large parts. Larger parts require multiple systems. A second system under development uses a video camera and a computer image on a CRT. Software provides the ply boundary information to the CRT and the video provides the actual position. The operator looks at the CRT while aligning the ply to the CRT image. It is believed that none of these systems are used for even limited production.

Automatic Tape Layup

This technology is in widespread use and is probably the most frequently cited example of composites automation. These machines are primarily located in factories that make relatively large, mildly contoured parts. The machines are generally furnished by Milicron and Ingersoll, with head designs which originate at Grumman and Vought. Some of these tape layers have also been equipped with water jet cutters and stitching heads. One has been converted to fiber placement. This conversion consisted of a head change for running 12 individual tows, major software additions, and added heat control function hardware.

The Japanese use tape layers for some of their large parts. The tape layers are U.S. made and run the delivered software. The gap and overlap criteria are similar to those applied to U.S. made parts. The tape layers appear to run with less human intervention and with fewer stops than they do in the U.S.

Current tape layers put heavy demands on raw material suppliers in terms of tack, tape width, release paper adhesion, and material splice locations (or lack of splice). A cassette tape layer has been introduced, but is not in widespread use. It was designed to alleviate some of the material demands by separating the cutting and laying into two operations.

Tape laying research is an evolutionary, not a revolutionary, process. The major areas of interest are in contact show material, cutting improvements, and more user-friendly software. Some efforts are being made to do real-time quality assessment using line scan cameras and oblique angle strobe lighting. There was at one time a major effort to tape-lay thermoplastics. However, the overall emphasis on thermoplastics has dwindled. Most tape laying of thermoplastics involved hot shoes or laser welding. Some PEEK work was done using an amorphous film carrier, which became molten material when heated. This severely limited the temperature capability of the system, but did not provide good laminates without subsequent autoclave compaction. Both Milicron and Ingersoll are now emphasizing fiber placement. Milicron has developed one machine and has orders from Boeing. Ingersoll will be entering the market in 1993.

Ply Cutting and Stacking

These technologies support the hand layup process. Ply cutting uses reciprocating knives, ultrasonics, lasers, reciprocating chisels, and most recently, water. All of these methods and also textile methods, such as steel rule dies, are in use in the U.S. The various methods have the advantages of speed, sharpness of inside and outside corners, multiple ply cutting, and the ability to cut very close to the fiber direction. Labeling the ply is also different on the various machines. The labeling usually is dictated by the next operation, which is clearing the cutter bed and sorting the plies. If a person is clearing the bed, the labels are alphanumeric and the nesting program has been adjusted so that all the plies in a stack are in close proximity. Some cutter beds are 60 inches wide and 60 feet long. Clearing and sorting can be a labor-intensive operation unless plies in a stack are within a few feet of each other, and remakes or add kits are at the head or tail of a table. If the plant has automated sorting, the label is usually bar coded. A few use alphanumeric character readers, but they are generally unreliable. Full automation of ply kitting has had many unsuccessful and expensive attempts. The purpose of automating the sorting and stacking job was to have no human intervention after the bar code was read. The combination of numbers of plies, ply kits, ply sizes, and speed demands has doomed most of these processes. The most successful attempt used bar codes and software to display the bin number and sequence in the bin. The person must then place it in the proper position. In most high volume operations, kits are packaged in heat-sealed poly with bar code identification. Most operations are just-in-time; therefore kits are not frozen prior to use. Some automated storage and retrieval is used to deliver kits to the workcells. This is prevalent in operations that are highly paperless.

The Japanese use ply cutting machines to support their hand layup process. These machines are all U.S. made and are running the delivered software. Nests looked to be more efficient for scrap reduction. This could be due to a more stable nest,

possible because fewer plies were scrapped; another reason might be that the operators are willing to search the full bed to complete a kit.

In the area of research, major emphasis is on improved software and links to various CAD systems. Potential exists for some improvement from automated sorting, with IRADs looking into systems similar to mail sorting systems. Automated flat ply collation is being done by Boeing and by others on a limited basis. Two types of machines have been built to pick up plies and roll them into place. One system cuts the plies without release paper on either side, removes the ply with vacuum handlers, sorts the ply into hundreds of trays and then places the plies directly on a flat plate tool. The flat plate tool rotates with the pick-and-place arm taking care of X and Y translation. The other machine is built for Boeing and only takes the cut ply, orients it, places it, and does a small amount of debulking. A limited amount of work is continuing on these systems.

In Japan, all three of the "heavy industries" companies (MHI, KHI, FHI) showed interest in ply sorting and kitting. However, it seemed that no work was ongoing in this area. This is an area where cooperative efforts between the U.S. and Japan could take place to vigorously seek low cost methods.

Filament Winding

This technology is used to apply more composite material than all other techniques combined. It is well suited for pressure vessels, therefore it has primary applicability in the missile business. Both intercontinental and tactical missile cases are built using this technology. Glass, aramid, carbon and boron fibers have been or are being wound. Wet winding is the most prevalent technique, utilizing resins with room temperature viscosity in the range of 2000 cps or less. These structures have void contents of 3 to 10%, with resin contents of 40% by volume. Winding with prepreg tow is used for structures that require higher temperature performance limits, and that also demand lower void contents to sustain loads other than tension.

Filament winding has been combined with other fiber application methods such as hand layup, pultrusion, and braiding. Classic filament winding involves a spindle with a carriage or carriages to apply hoop and helical fibers. Compaction is through fiber tension. Resin content is now primarily metered. The machines are generally all computer controlled with up to six axes independently monitored. The additional axis comes into play at the fiber turn-arounds. The extra head axis allows for better placement of the band, and more uniform band width.

Filament winding has been used to wind large wind-machine blades up to 150 feet long. Rectangular tubes with hand-laid axial fibers have been split and used for back-to-back channels. These have been used for floor beams. Filament winding is still in widespread use for pressure vessels and other missile components. Some

helicopter rotor blades are still manufactured utilizing highly modified filament winding processes.

Winding engine nacelles has been done for many years, but is now being done with prepreg tow. The MD-11 large center engine nacelle is made using hand layup; however, attempts are underway to filament wind.

In Japan filament winding is performed using U.S.-built machines. Most applications observed by the team used prepreg tow. Tooling is unique, utilizing mandrel expansion for pressure applications, and a disposable outside diameter rubber sleeve for surface finish.

Some tape winding is performed using modified filament winders or Japanese-built machines. These machines are making contoured broadgoods for subsequent cure in an outside mold line tool. Figures 1.3 and 1.4 depict a typical wrap machine and the resulting panel.

As far as research is concerned, filament winding is a very mature technology with innovation and technical advancement at very low level. Computer hardware and software continue to change as robotic advances are made. There are few filament winding machine suppliers left in the U.S., therefore most of the modifications and improvements are being made by the users. Wet winders are being improved in resin control and fiber wetout. In the wet wind process utilized in line impregnations, wetting is the speed-limiting factor. The most ambitious in-line system uses an alpha source and detector to measure the mass before and after an impregnation orifice. The orifice area is controlled by an inflatable metal ring. The total system is a closed-loop, computer-controlled network, capable of variable resin contents. Some winders preimpregnated the spool in a vacuum chamber prior to installation on the machine.

Tow Placement

This technology is a combination of filament winding and tape laying. It probably has the most promise as a practical automation tool for skins. There are currently four machines in the U.S. industry. This technology utilizes preimpregnated tow. The fiber placement machine tracks along the tool surface, laying up to 36 tows of preimpregnated tow. The fiber is laid with essentially zero tension; therefore tool concavity is possible. All current machines, except one, include spindles. The machines with spindles handle closed-form as well as flat plates. The only company building production or semi-production parts is General Electric machine. That unit is building blades for the GE-90 High-Bypass engine. Hercules has built numerous CRAD parts. The Hercules technology seems cost-effective and produces structures consistent with hand layup.

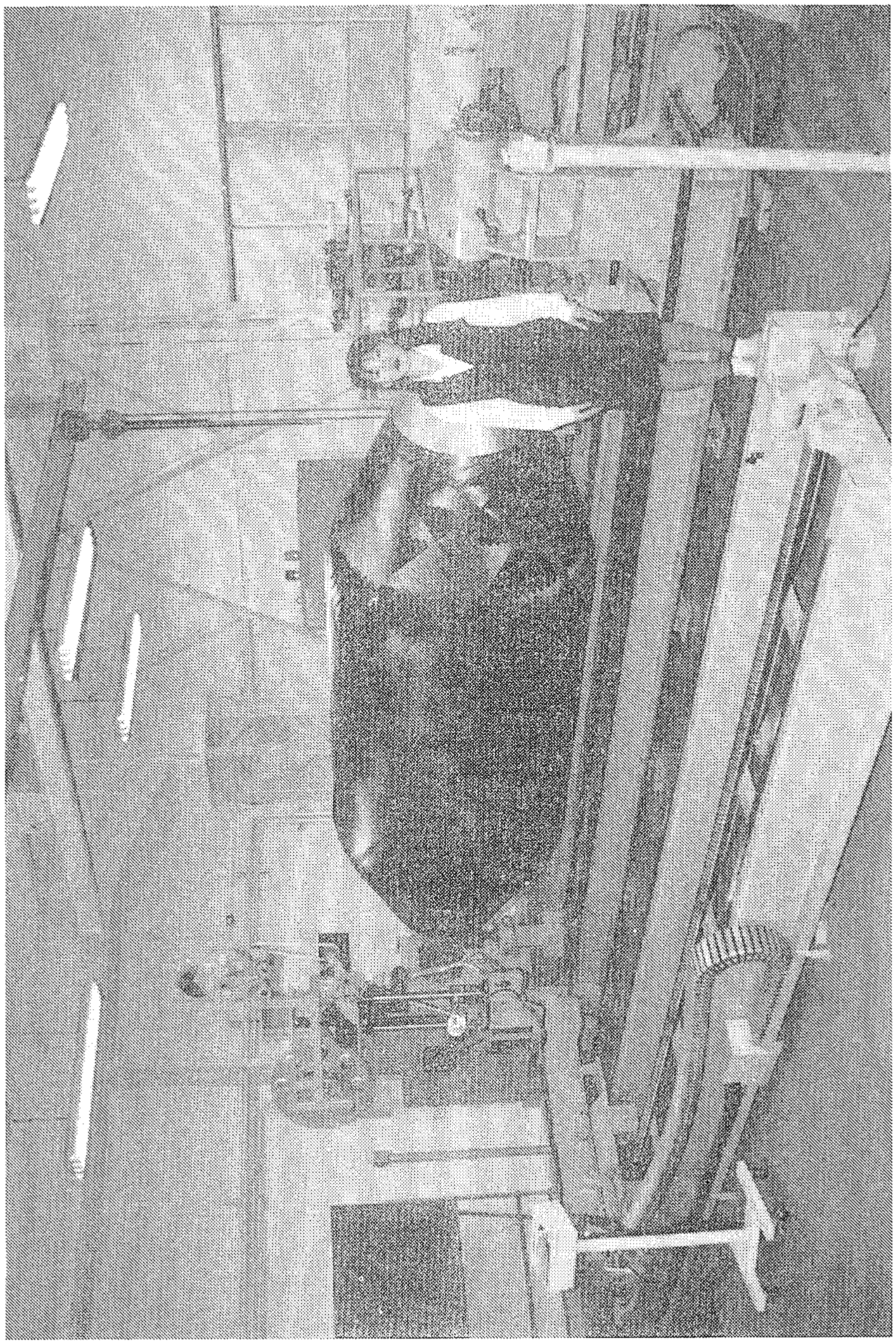


Figure 1.3. Tape Winding Device

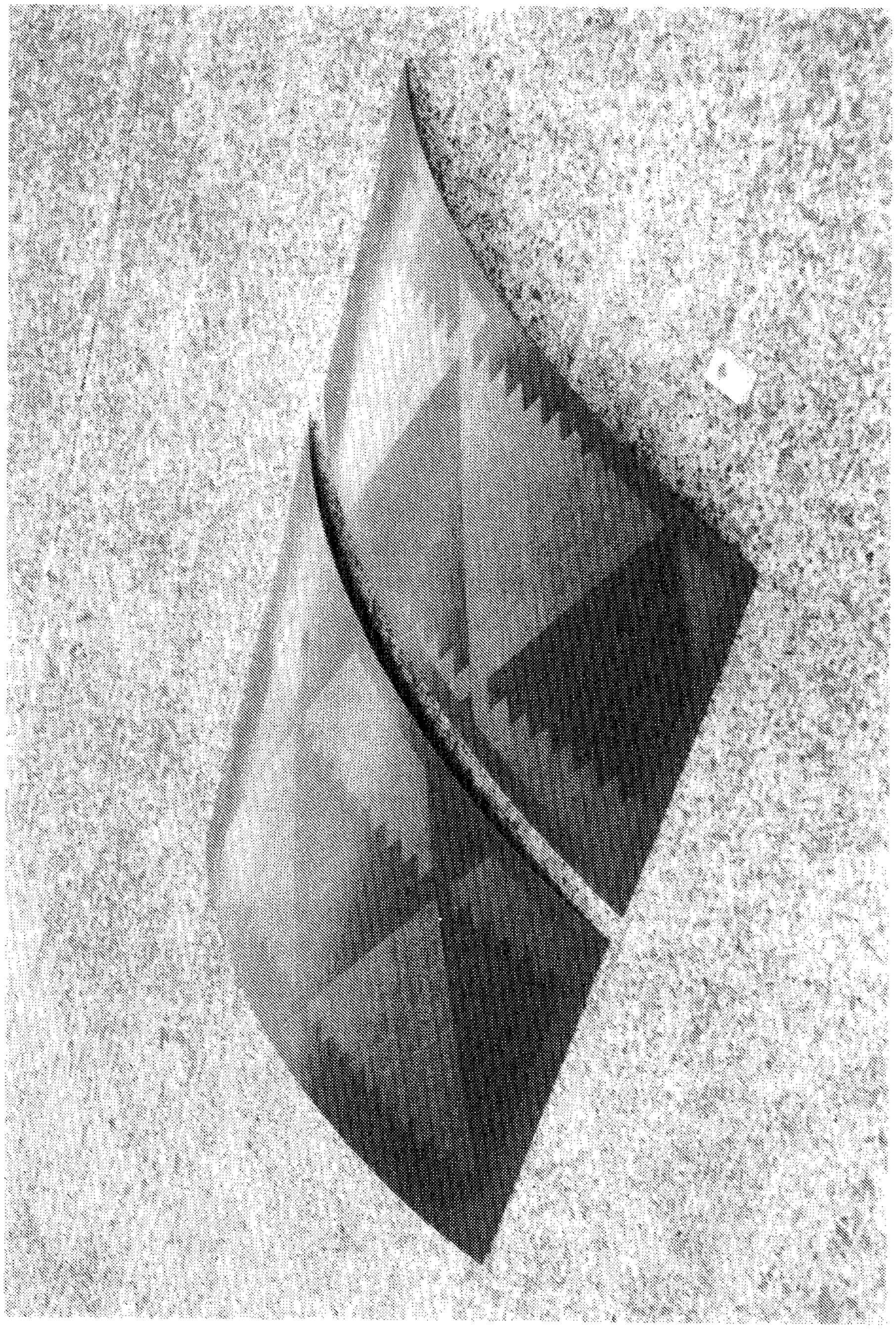


Figure 1.4. Full Scale Panel

The technology has been used to produce skins with substructure embedded in the tool and the part co-cured. This concept is inside-mold-line tooled. The technology has been used to produce contoured skins on a mandrel tool which are then removed. The compacted skins are placed in an outside mold line tool and stiffeners are placed on the skin and co-cured in the outside mold.

Fiber placement has also been used to fiber-place box substructures with additional tooling added and the skin fiber placed over the uncured boxes. Still the largest cost is forming the substructure. The most automated process for the substructure is the Boeing channel laminator. It uses tape-laid ply packs, and hot drape-forms the beam.

Tow placement is still a curiosity in Japan and did not seem to be well understood. There were many requests for visits to Hercules to view fiber placement and discuss technology transfer.

The forming of stiffeners was briefly discussed. One project for the forming of closed free edge blades was observed. It is called an omega stiffener and is shown in Figure 1.5, along with a sketch of the machine that makes it. These stiffeners exit the process uncured and enclosed in the silicon rubber cure mandrel.

The area of fiber placement is ripe for extensive research. The fiber lay-down head is branching into two areas of focus. The first is a complex head that forms the tow to the proper thickness and width in the head. The second is the type of head that requires tow from the material supplier at the proper width, which in turn simplifies the head function, but increases the material costs.

Other areas of research concern expanding the capabilities of fiber placement to lay thermoplastic and polyimide. Current thermoplastic work involves laser heating at the lay-down point. This concept is also being explored for thermoset. The material would not cure at lay down but would be well advanced through the viscosity curve. Work is being done on conformable rollers and on reducing the minimum course length, which is currently about six inches.

Pultrusion

This method is primarily low technology; however, there have been some high-technology enhancements to the pultrusion process. Feeding in plus and minus bias weave fabric in place of the normal mat feeders is being used. The resins used in combination with some changed die geometry are allowing higher Tg matrix systems to be used while still having reasonable pulling power.

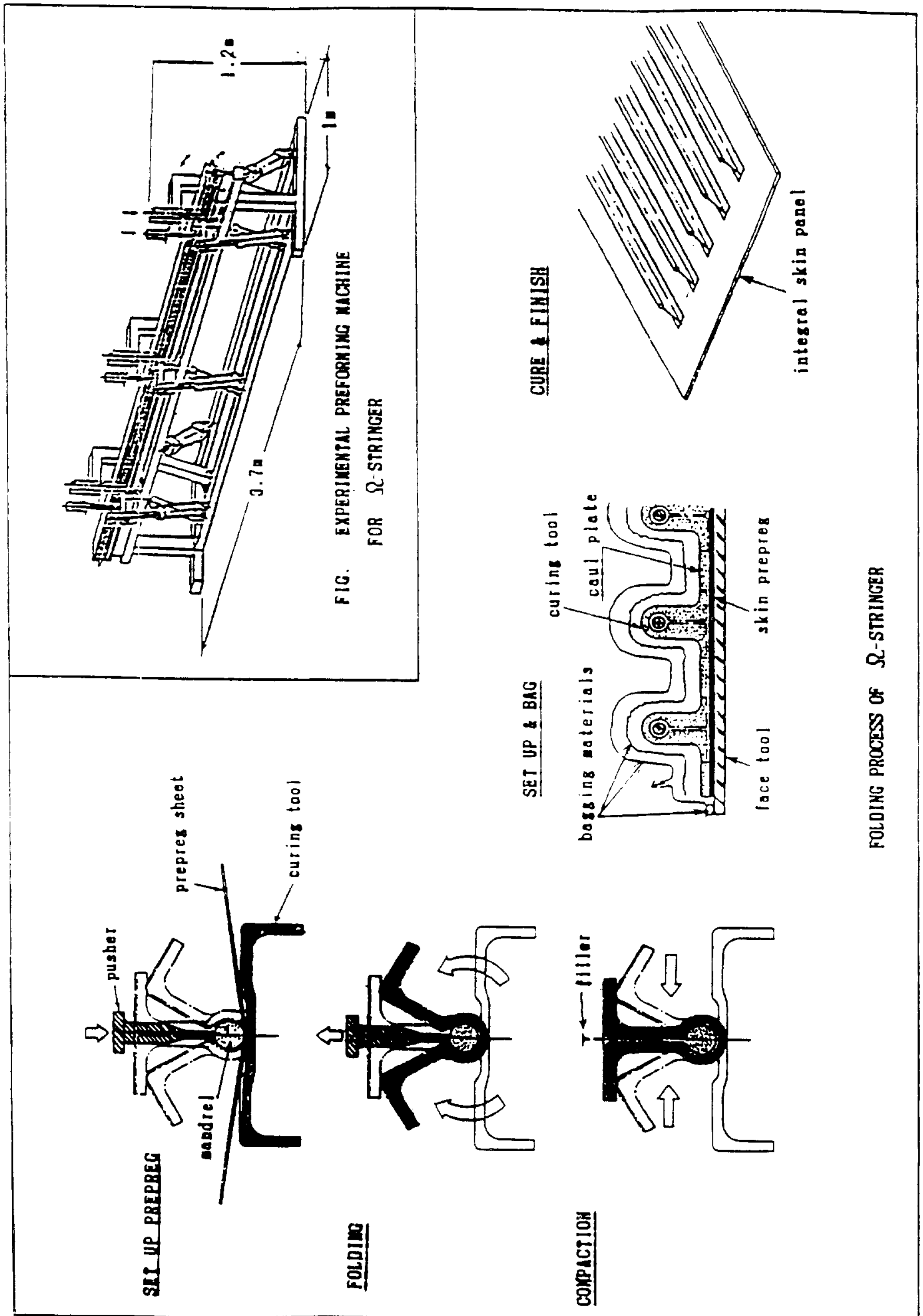


Figure 1.5. Folding Process for the Ω-Stringer

Research. When considering low cost, one thinks of continuous processes. Pultrusion is one of the few continuous composite fabrication processes. Research is aimed at introducing carbon fiber, epoxy matrix, and fiber orientations other than zero. A definite objective is the pulling of B- or C-staged structural members for subsequent forming and co-curing. The Xerkon process produced C-staged stiffeners, which were subsequently formed and co-cured to the V-22 fiber-placed skin.

Two research projects were observed in Japan which could be called pultrusion. Both seemed destined to produce very slow process speeds, but that slow speed may allow a very reliable machine. One machine is being researched to build carbon epoxy tubes for the Japanese space station. It is a typical MITI research project in which a research company is formed for a period of 10 years. The company employees come from the various companies that have an interest in the project. This particular research company is led by Mitsubishi Electric. Figure 1.6 shows the machine. It is similar to a driveshaft machine patented by Hercules.

The second pultrusion project is being performed by an independent Japanese company (JAMCO) which has developed a machine for pultruding curved and straight "L" and "T" stiffeners. This machine is shown in Figures 1.7 and 1.8 pultruding a "T" shaped frame. This again is a slow process that uses carbon/epoxy prepreg tape and fabric. This same company uses a similar process to produce flat, glass faced, cored panels. Both of these processes would appear undesirable to an American, who would immediately ask: "How many pounds per hour will it lay?"

Resin Transfer Molding (RTM)

This technology has a potential for cost reduction equal to that of fiber placement. Currently, we know of no production application of RTM in aerospace. Non-recurring costs for the tool are very high and recurring preform costs are high. The resin content requirement at 40% by volume also slows the process turnaround.

Research. Aerospace applications of this technology are going in various directions. Cheaper preforms is one avenue. Lubricating the preforms to allow the mold to close over the bulk factor is another major thrust. Tooling which has a larger volume during resin transfer and then seats to final position after filling is being pursued. Some research is actually targeting a structure as large as a wing skin with stiffeners.

This is another area of MITI interest. A "10-year" research company was created to thoroughly investigate the weaving of preforms. When a preferred concept is recognized, a machine is to be developed which will economically produce the preform. This company is currently six years into the 10 years, and is presided over by Mitsubishi Electric. See Figures 1.9 and 1.10 for examples of weaves.

FABRICATION
Combined Process of FW and Pultrusion
(Circular or Square Cross Sectional Tube)

PERFORMANCE
High stiffness, Thin Wall and High Precision
(Thickness 0.5 to 1mm, Vf 60% above)

Proto type
FORMING EQUIPMENT
Designed and Assembled

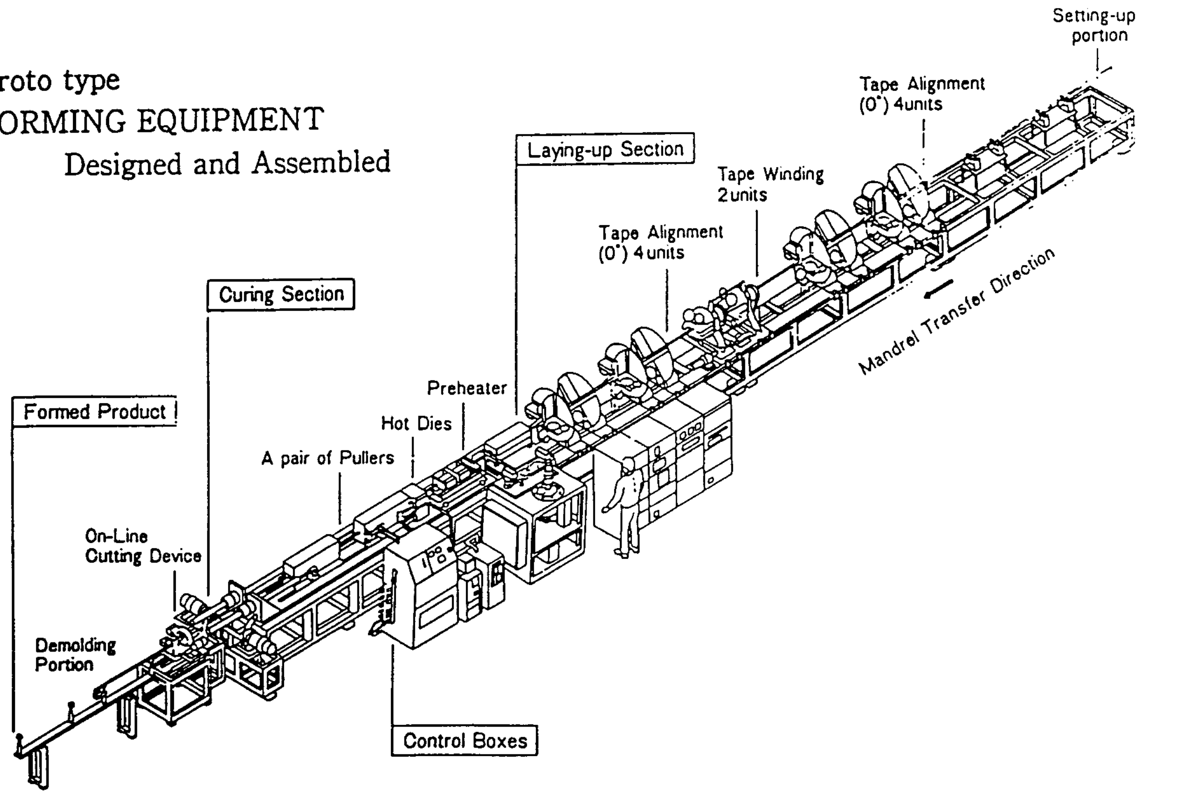


Figure 1.6. Continuously Formed Graphite/Epoxy Composite Tubes for Large Space Structure

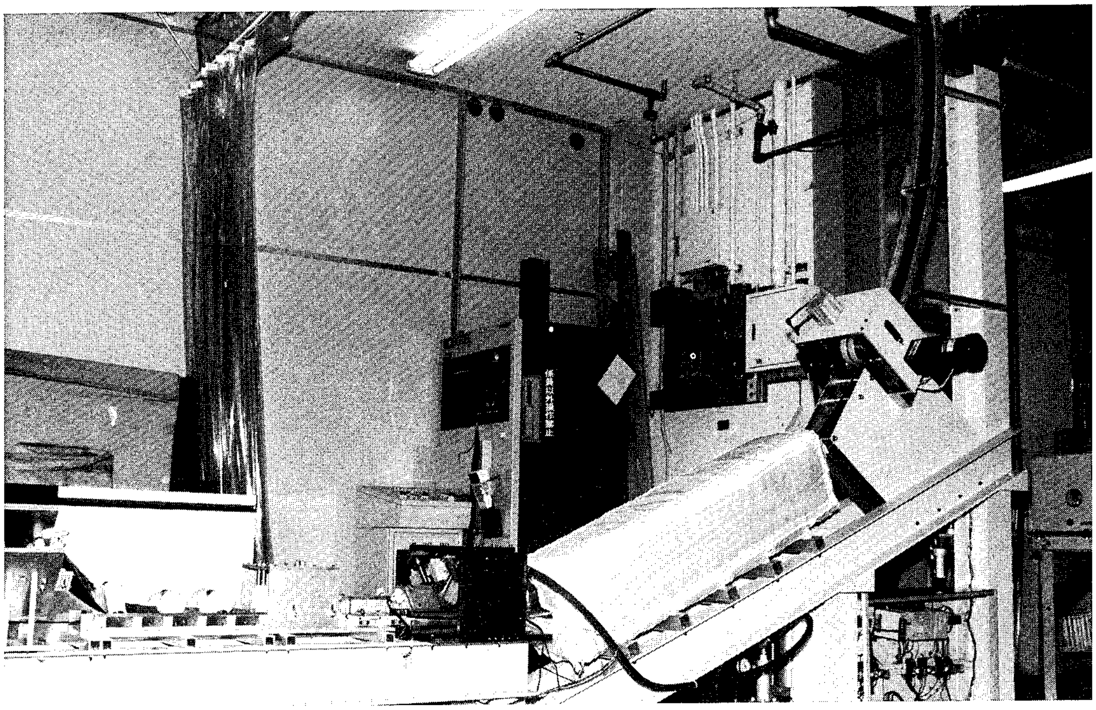


Figure 1.7. JAMCO's Continuous Curved Pultrusion Machine (side view)

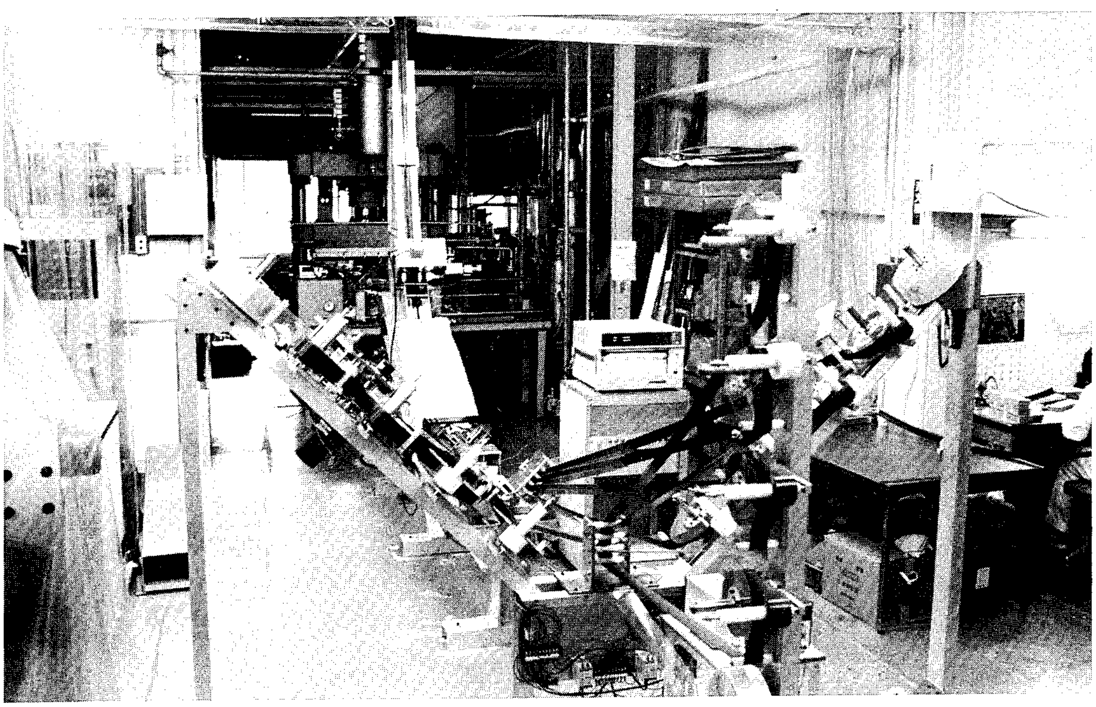


Figure 1.8. JAMCO's Continuous Curved Pultrusion Machine (front view)

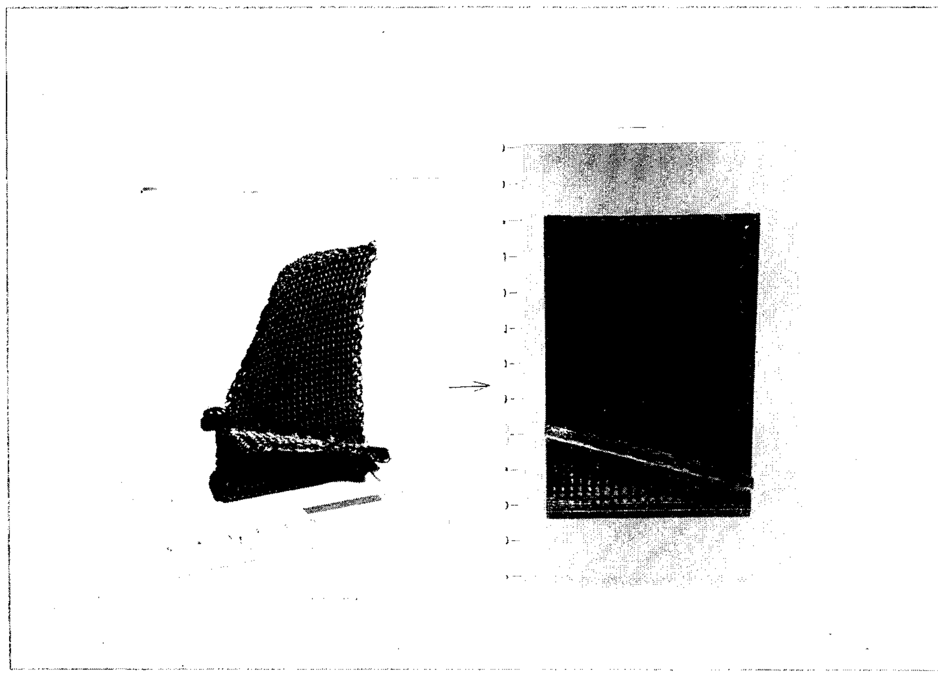


Figure 1.9. 3-D Fabric → RTM (1)

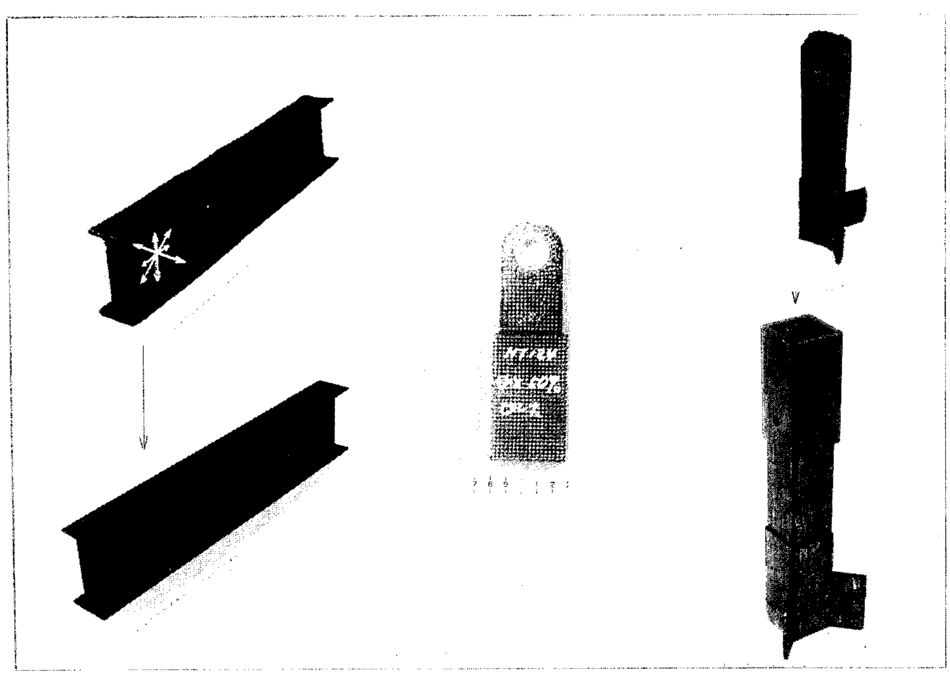


Figure 1.10. 3-D Fabric → RTM (2)

Thermoforming

This technology appeared to have applications during the prime of thermoplastics in aerospace. In Japan there is still a major emphasis on thermoplastics, and some 10-year projects still have three to five years to run. Double diaphragm forming using aluminum carrier sheets was all that was observed. All other thermoplastic work was flat.

There are some promising research projects in the U.S. which are modeling and forming thermosets using rubber diaphragm carriers. We saw no comparable work in Japan.

Long Discontinuous Fiber

This material has not been readily available to aerospace. It was promoted for use in a thermoplastic matrix, in order to allow hot thermoplastic/LDF to drape without buckling. No production aerospace parts are currently produced, and material qualification data have not been established.

Research. This material is now being offered in a thermoset matrix. The objective of this research is to find a suitable application for this material. It may have an application as inner stiffening panels on doors and covers. It is also being considered for the web of tall beams to form corrugations or for stiffness.

The Japanese are familiar with long discontinuous fiber; however, no thermoplastic or thermoset projects were observed.

RELATED TECHNOLOGIES

Curing

The aerospace industry is primarily using autoclaves, ovens, and microwaves for curing. The use of ovens and microwaves is somewhat confined to wet-wind missile production. Ovens are also used to cure the so-called "room-temperature-cure" composite tools. Autoclaves are the primary production curing tools for all users of prepreg.

Curing in Japan is generally performed using autoclaves. Few of the autoclaves observed by the team had fully automated and programmable controls. One item of particular interest was the close research tie between tooling and curing. Tool development makes full use of thin film pressure transducers, dielectric resin viscosity sensors, and embedded thermocouples to produce tool and cure processes which are reproducible.

Research. Autoclave research centers on improved control, critical parameter feedback transducers, tool heating, and improved vacuum bags. The Japanese are working to eliminate the need for autoclaves, researching techniques such as "cure-on-the-fly."

Tooling

Tooling has more potential for improving part quality and reducing part cost than any other technological area. Tool design and part design are intimately linked. The key to success on a large majority of the composite CRAD and IRAD programs is related to tooling. Tooling for aerospace composites could be considered a benchmark activity of its own.

One of the most significant differences noted between the U.S. and Japan was in the area of tooling. This ties in with the ability to design for manufacture and assembly. Figures 1.11, 1.12, and 1.13 depict the evolution of co-cured complex components. In the U.S. we have not attained this level of unitization for many reasons, including the reluctance to rely on an untrained workforce to operate complex tooling and processes. The use of matched metal tools and totally co-cured structures in production situations was observed by the team for the first time in Japan.

FUTURE COMPOSITES MANUFACTURING TECHNOLOGY

A major new breakthrough in composites manufacturing technology is not likely to occur in the foreseeable future. Most likely, there will be a series of improvements to existing manufacturing technologies, and manufacturing concepts already generated will be proven. For composites to become competitive with metals, cost reduction has to occur in three areas: nonrecurring costs, recurring costs, and direct operating costs (DOC) (e.g., durability, maintainability, reliability, and repairability). IPD will continue to infiltrate all the disciplines for improved efficiency in design and manufacturing. It is expected that DOC will become a much bigger issue as many aircraft with composite components enter revenue service. There will be doubts as to whether composites will ever become cost-effective for commercial use; however, these doubts can be assuaged by the facts. The reduction in manufacturing cost realized by improved technology will lose its value if it is offset by an increase in nonrecurring costs and DOC. Thus, life cycle cost analyses should be conducted along with the traditional trade-off studies of weight vs. strength and stiffness vs. cost.

Some of the manufacturing technology developments expected to occur in the foreseeable future are described below.

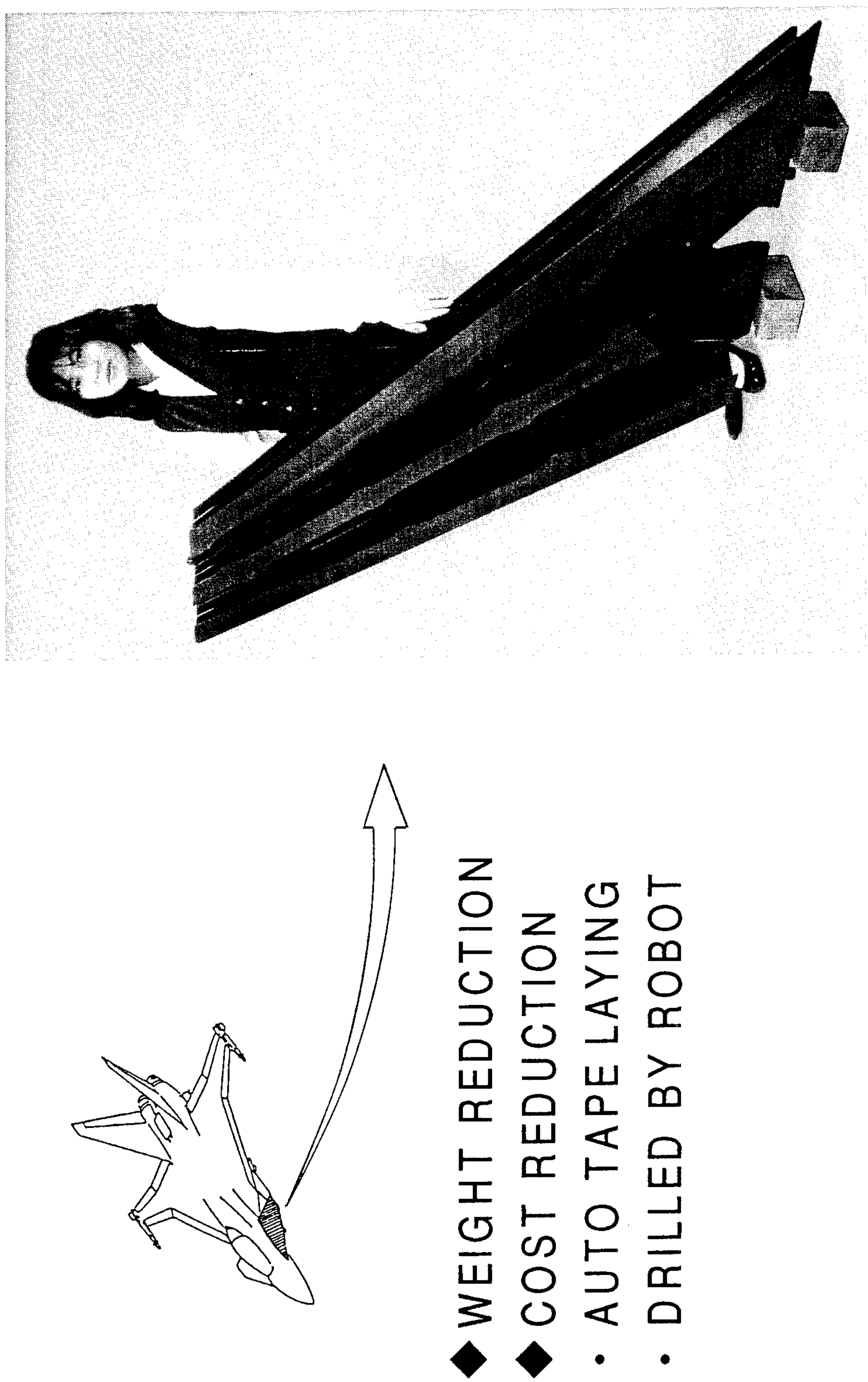
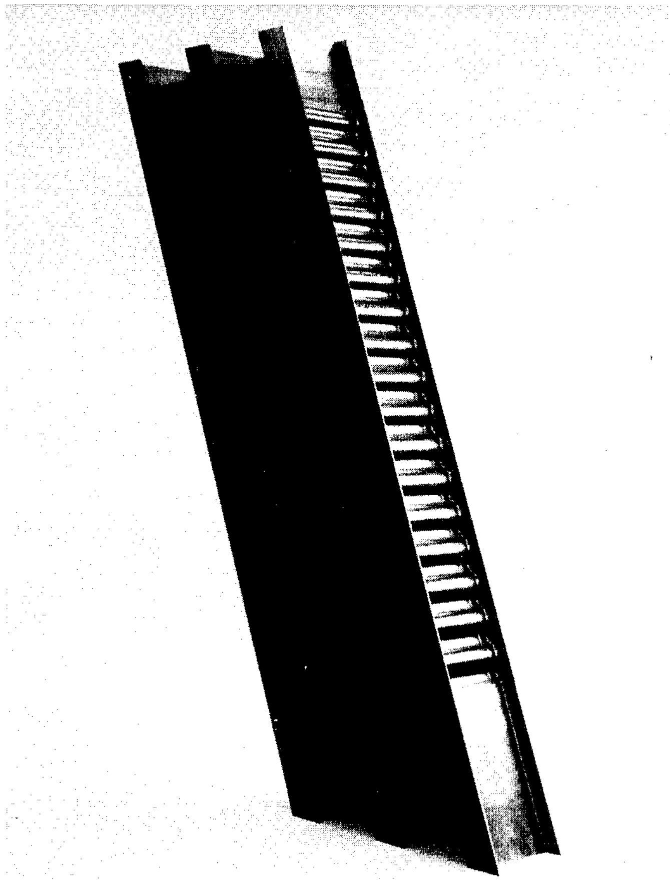
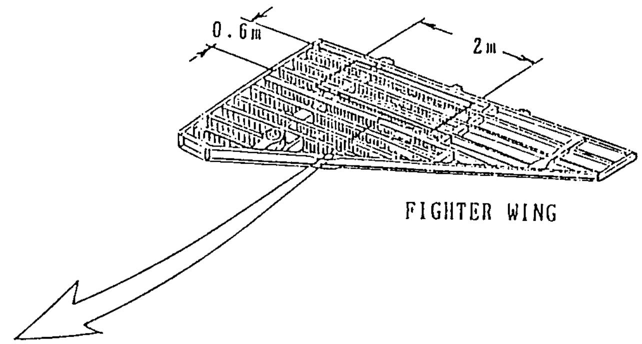


Figure 1.11. Co-cured Canard Box Structure





MATERIAL

HIGH STRAIN GRAPHITE/EPOXY : SKINS, SPARS, RIBS

RESULTS

- ESTABLISHED FABRICATION METHOD OF SINE WAVE SPAR AND INTEGRAL STRUCTURE
- OBTAINED STRENGTH DATA OF SINE WAVE SPAR
- CONDUCTED STIFFNESS TEST OF BOX BEAM

Figure 1.12. Research Program of Sine Wave Spar and Box Beam

MODEL	New Fighter Program
TYPE	Integrated structure of Gr/Ep skin, multi-spars and ribs
SIZE	160" (L) x 80" (W)
FAB. METHOD	Co-curing process Gr/Ep skin, spars and ribs are all cured at one time
TOOL	Combination of steel and Gr/Ep
REMARKS	Successfully static and fatigue load tested in 1987 JDA Contract in 1985

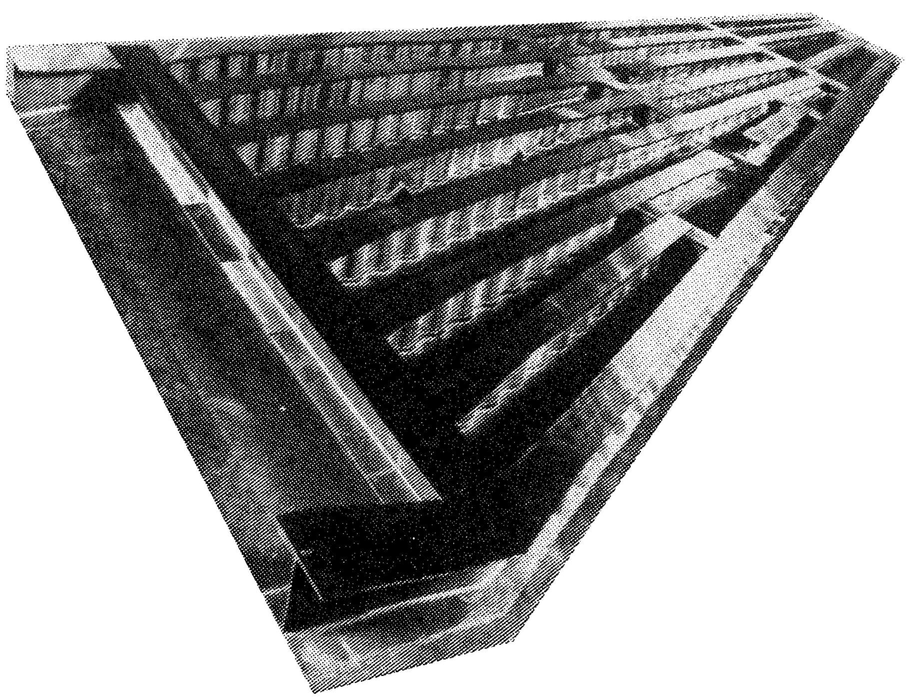


Figure 1.13. Wing Torque Box

Stitched/RTM

Small to medium size stitched/RTM parts have been fabricated with some success; however, the fabrication of complete wing skins and box by this method is a long way off (Note: this method is not cost-effective for small to medium size thin parts; to take full advantage of this method, the parts must be thick and large). For this technology to be incorporated into wing design, an appropriate automatic stitching machine has to be developed. This machine must have the capacity to handle various skin thicknesses, ranging from less than 1/4" to more than 1", and with many different shape and thickness stiffeners attached to it. Concurrently, a new cost-effective resin system specifically for RTM application must be developed. Along with stitched/RTM manufacturing technology, other issues (e.g., repair method, certification, and joints) must be addressed and resolved.

Filament Winding

This is a mature manufacturing technique which has been in existence for a long time. Improvements in automation, speed, variable thickness, pad-up insertion, consistent quality, flexibility in fiber orientation, control of resin and void content, and shapes other than cylinders will be seen before more versatility appears in application. A combination of robotic and traditional filament winding (with seven to 10-axis) system is already available in crude form. If this system is perfected, it will be able to wind complex non-axisymmetric shapes, such as T and elbow shapes. One of the most critical requirements for a successful implementation of this method is controlling the tension of the deploying filament during the winding processes. This critical problem may be quickly solved with the aid of powerful computers.

Pultrusion

This method has the potential for cost reduction, but current technology is limited to constant cross sections and is restricted in fiber orientation. Pultrusion is not as popular as metal extrusions. Metal extrusions are attached to other structural members, such as skins and webs, by hundreds and thousands of fasteners and rivets. This method of assembly is not acceptable for composites, where the strong trend is to eliminate fasteners. Consequently, for pultrusion to become an acceptable and popular composites manufacturing technology, it must be possible to pultrude complex multi-element cross sections, such as J-stiffened panels and constant airfoil sections. It is expected that a new technique for making tapered sections with variable thickness and even variable shapes will be available within this decade; significant progress has already been made toward that end in the last few years. Another new development is curved pultrusion.

Preforming and braided pultrusion are variations of pultrusion for special applications. New developments can be expected in these areas.

Continuous Sandwich Panel

This method is already used in production. However, it is limited to making flat constant sandwich panels. Future improvements will increase speed of fabrication and quality. Floor panels, galleys, and partitions are the major uses of flat sandwich panels. Therefore, there is no need for a technology which produces a continuous sandwich panel of complex shapes and variable thickness.

3-D Weaving

The advantages of 3-D weaving are widely known, but the cost has been prohibitively high. A few automated and semi-automated systems have been created or are under development to reduce cost. Although 3-D weaving is still in its infancy, it has the potential to replace expensive titanium fittings, hinges, engine blades, etc. In addition to reduced costs of weaving, improvements in curing will be seen.

Mechatronics

Aircraft components in general and composite parts in particular have been known as hand-made custom products as opposed to automotive and electronic products. Full automation is probably not cost-effective for aircraft applications because of relatively low production rates. However, a semi-automated method using mechatronics may be a viable option for aircraft manufacturing. Currently, mechatronics is not a fully developed manufacturing technology, but its development should be followed with keen interest.

Automatic Tape Layup Machine

Significant progress has been observed in ATL technology. Both speed and accuracy have increased tremendously when compared to early ATL. Advancements in computer technology (hardware and software) have influenced ATL. Along with improvements in speed and accuracy, the capability in size of layup area has also increased. Although a new breakthrough is not expected to occur in ATL technology, improvements will be incremental but continuous.

Automatic Ply Cutting Machine

This technology has made significant progress in recent years. Three different methods of cutting are used for an APC machine: mechanical, laser, and water. Each has its own advantages and disadvantages. No new breakthroughs are expected in APC technology.

Tow Placement

Tow placement is relatively new and has received considerable attention in recent years. It combines the advantages of ATL and filament winding. Tow placement can fabricate complex-shaped structures without limitations on fiber angles. It has the potential to reduce production costs significantly. Under the Air Force MANTECH and NASA ACT programs, this technology has proven its worth; however, its use at high production rates still remains to be seen. Future developments include optimized control systems, head position feedback, and in-process inspection for fast, accurate and high quality parts production.

Co-Curing Technology

The advantages of co-curing technology are numerous, but complex tooling, high risk, and the difficulty of adapting it to high production rates inhibit widespread usage. Continuous improvements in prepreg materials, tooling concepts, quick turnaround, and quality consistency may result in the elimination of those hurdles.

Forming, Stamping, Injection Molding, Rolling

These manufacturing methods have great potential for high volume production applications, especially when combined with the use of thermoplastics. Application is limited to small to medium size parts. Sporting goods and industrial products will benefit from this group of technologies.

Repair Technology

Repair technology is gaining more attention. Operators of aircraft are discovering that composites are showing a better service record than are metals, mainly due to their better fatigue and corrosion resistance properties. But at the same time composites are more prone to impact damages, which increases the importance of repair. As new generations of aircraft with tremendous amounts of composites enter flight service, both commercial and military operators will demand improved repair technology. Both the cost of repairs and the down-time resulting from the complexity and special facility and equipment requirements are putting severe demands on repair technology. Current repair technology is not satisfactory, and improvements are necessary.

Material Technology

Several years ago, the most popular topic in material technology was the "tough resin" system, followed by "thermoplastics." Today's popular materials are "stitched preforms," "tow placement," and "woven textile." Contrary to the original belief that thermoplastics greatly reduce manufacturing cost and time, the observation is now

being made that thermoplastic parts cost more and are difficult to produce. In fact, some of the material suppliers are considering discontinuing thermoplastic production. It is still early to predict whether stitched preforms, tow placement, and textile will replace prepregs by the end of this decade. The next three years will be crucial for these so-called new advanced material systems to become dominant. It all depends upon how well these new materials can be adapted to a production mode where cost, quality and manufacturability play important roles.

Operating temperatures of the High Speed Civil Transport will be 250°F to 450°F, depending upon the location of the structure within the aircraft. Epoxy systems alone cannot handle this temperature range. The race for a new material system has already begun, and it is still too early to predict what will happen in an intensely competitive market. Candidate materials are polyimides, bismaleimides, metal matrix, ceramic matrix, etc.

SIGNIFICANT FINDINGS FROM THE VISIT TO JAPAN

The Japanese aerospace industry does not possess superior manufacturing technologies for composite structures. Most, if not all, of the manufacturing technologies the Japanese possess are the same as, or are variations of, those possessed by the U.S. aerospace industry. Yet, using the same manufacturing technologies, the Japanese companies are capable of making production parts of better quality, on schedule, and with less cost in many cases. Why? The answer may be found in areas other than technology:

- Japanese companies develop fabrication techniques and know-how and then voraciously implement them. For example, one company developed a bagging technique to conform specifically to a complex part and then created a detailed procedure for repeatability and producibility.

- People are considered the most important asset in a Japanese company.

- Production workers are trained, tested (sometimes in writing), and retrained and retested to increase their skill level and value.

- Higher standards and goals are set. For example, less than one percent error was not considered good enough and they are now working toward the goal of zero defects.

- The Japanese have a policy of putting money and effort up front to prevent problems down stream. They spend time, money, and effort on tooling, process, procedures, systems, and people to virtually eliminate production and in-service problems.

- When the Japanese decide to incorporate a certain technology, they do so with determined thoroughness and voracious detail. That's their culture and the way of thinking.

- Manufacturing/production gets the highest priority. When a production problem arises it gets the immediate attention of all the concerned departments.

- Their production area management is superior. One company incorporates a streamline/batch management system for increased efficiency and improved morale.

- Long range outlook is considered more important than short range profit. Unlike in U.S. companies, manufacturing engineers and workers are allowed sufficient time and budget to perfect fabrication techniques.

Although the manufacturing technologies observed in Japan are similar to those in the U.S., there are a few potentially cost-saving technologies worth mentioning:

- Large scale co-curing to reduce part count, fasteners, and assembly time
- Omega stringer reinforced panel
- Curved pultrusion
- 3-D and 2.5-D weaving, textiles, preforms
- Continuously formed thin-walled tubes

A qualitative evaluation of how each company fits into the composite picture is shown in Figure 1.14. The three "heavy industries" companies (MHI, KHI, FHI), which represent the Japanese aerospace industry, have essentially equal focus but have slightly different emphases.

Because of Japan's small aerospace market there is little opportunity for domestic production; thus, the Japanese are dependent on the global aerospace market. Well developed, long term, focused, *applied* research will eventually result in lower cost composite assemblies.

Extrapolating from Japan's current status and effort, thermoplastic and RTM/preformed structures may become cost-effective in Japan before they become cost-effective in the U.S., where the effort in those areas has slowed down in recent years.

Automation may take the form of slow, but highly reliable, low man loaded machines which can be run for 24 hours a day without any human intervention. This type of slow automated machine is acceptable in aerospace applications, where production rates are small, and high quality reliable products are required.

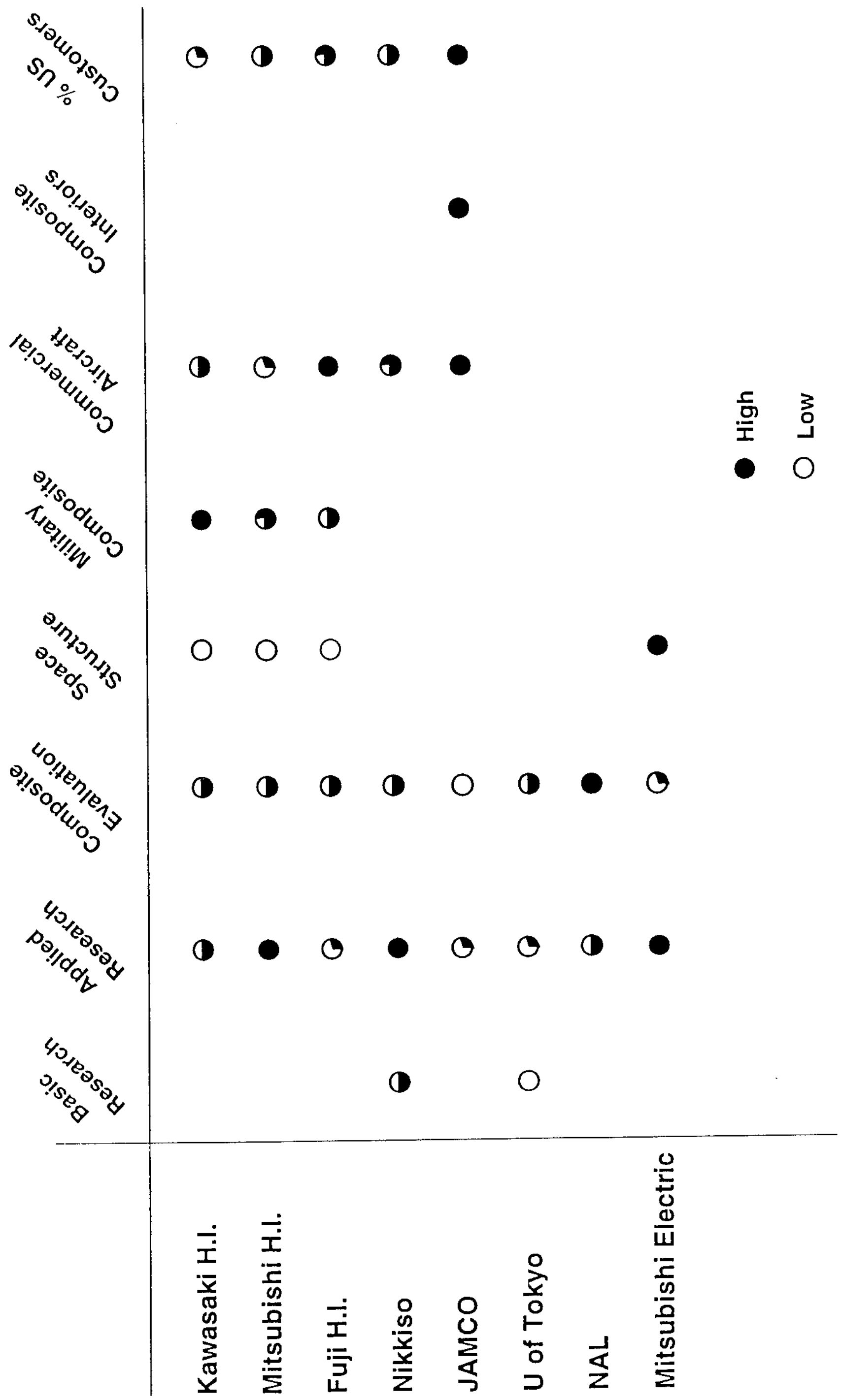


Figure 1.14. Composite Focus by Institution

Note: blank (no circle) indicates that the JTEC panel is unaware of any activity in that topic at that institution.

SUMMARY

Comparison of current manufacturing capabilities between the U.S. and Japan is summarized in Figure 1.15. In many areas, current U.S. capabilities exceed those of Japan. A notable exception is co-curing technology, where technology went beyond science and became an art, meaning that the skill of a master craftsman is essential for success.

It is clear that Japan's true strength in aerospace composites is not rooted in manufacturing technology but in other factors attributed to the temperament of the Japanese people and their culture. This means that Japanese advanced manufacturing techniques, such as co-curing, can be transferred to the U.S. only if other elements attributed to human factors are also transferred.

Contrary to expectations, no new breakthrough in manufacturing technology was found in Japan. Evolutionary rather than revolutionary improvements will be the trend of the future, and the Japanese are expert in achieving incremental improvements because of their determined thoroughness and respect for detail.

It has been a tradition for Japanese aerospace companies to cooperate with each other on a common topic or project for a number of years. Afterwards, each company develops its own unique fabrication technique. The aircraft industry in Japan is small and supported by the government as is obvious from its heavy reliance on military contracts (75%). There is, however, one notable exception to the Japanese cooperative spirit, and it can be found in the relationship between industry and educational institutions. Japanese industry sees educational institutions as suppliers of well educated, but not necessarily well trained, people instead of as suppliers of knowledge and technology.

The Japanese aerospace companies are aware of the potential market for composites and fully understand that "low cost" is the answer to a widespread usage of composites. They also understand that "low cost" does not come from advanced manufacturing technology alone. They see the term "low cost" from a total life cycle cost point of view -- "womb to tomb." Therefore, they are willing to spend time and money up front in order to reduce production, in-service, and recall costs later on.

The Japanese aerospace companies feel that cooperative effort with the U.S. is necessary for the promotion and expansion of the composites business. Therefore, most companies allow free access to their manufacturing areas and answer most questions candidly. Their willingness to cooperate with the U.S. and other countries

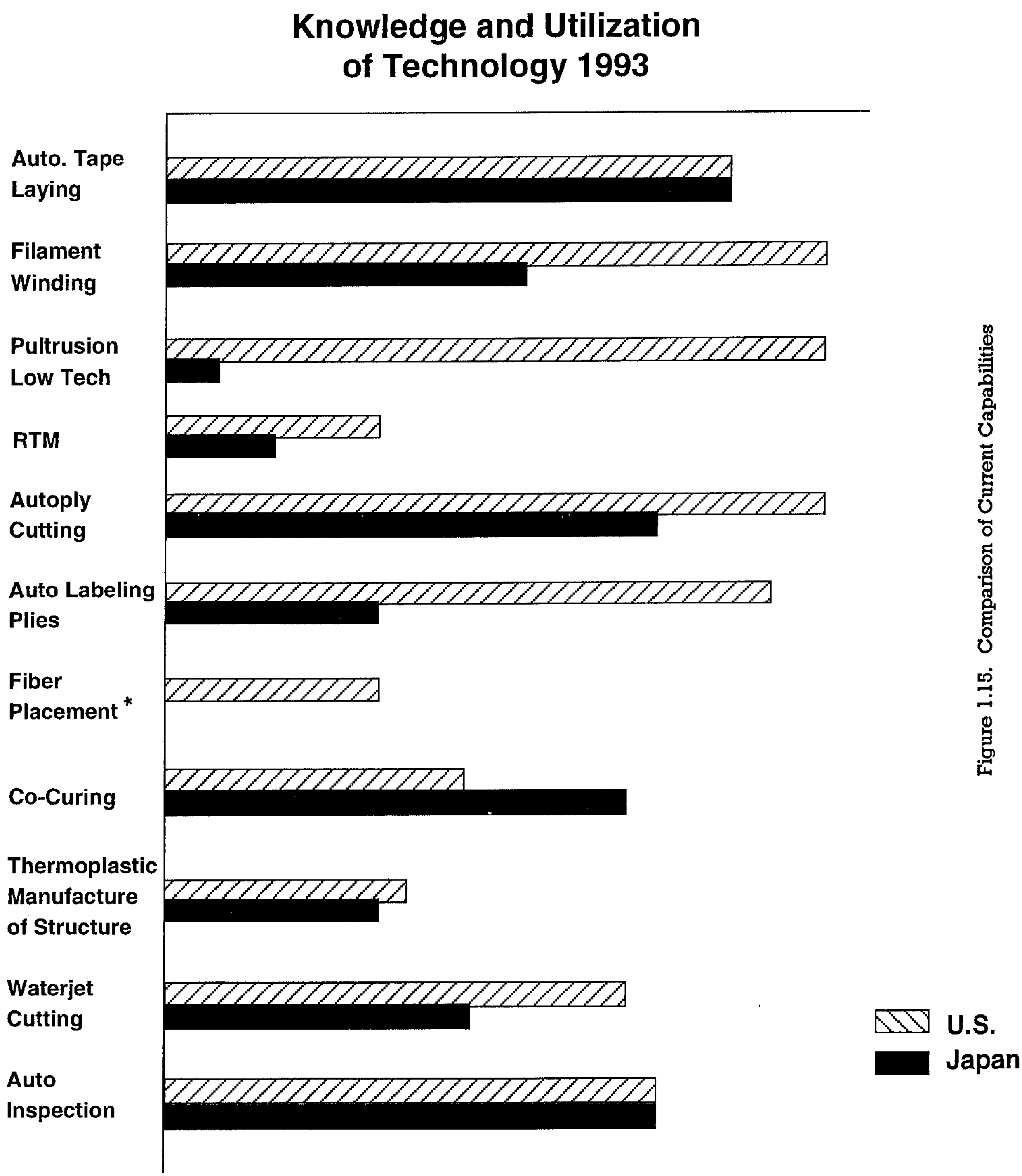


Figure 1.15. Comparison of Current Capabilities

* The JTEC panel is not aware of any fiber placement activity in Japan

is also reflected in MITI's policy for the future. MITI has clearly stated that its funding is available only for international cooperative programs. In other words, Japanese companies would not receive funding from MITI unless they have foreign partners. Cooperation between Japan and the U.S. has already begun with the transfer of Japanese technology to several American companies, notably MHI's sophisticated co-cure technology which was transferred to General Dynamics.

The U.S. and Japan have much to gain from each other. Now that the world is no longer dominated by the two military super powers, the sharing of technology by the two economic super powers (the U.S. and Japan together produce 45% of world GNP) is the formula for preserving the peace, stability, and prosperity of the world.

The economic failure of either country will undoubtedly bring both countries down and will eventually lead to world economic chaos; thus, the responsibility is enormously high for both countries. Accordingly, the U.S. and Japan must develop ways to cooperate.

CHAPTER 2

AEROSPACE APPLICATIONS

Moto Ashizawa
Dee R. Gill

INTRODUCTION

This chapter begins with a discussion of the relevance of the aerospace component of composites manufacturing technology. This is followed by a review of current global events that affect the aerospace industry, and in turn, composites technology. The body of the chapter reviews various aerospace applications of composites in both the United States and Japan. Cultural differences between the two countries are noted where they affect the approach to applied research, product development, and product manufacturing. For concluding remarks, a discussion is included on such key items as technology transfer, international collaboration, and partnerships and joint ventures, which are the keys for advancement and the expansion of composites technology and business in the context of growing economic globalization and the development of a borderless economy.

RELEVANCE

Many countries consider aerospace a strategic industry for reasons of national security, economic strength, and technological advancement. Therefore, it is understandable for a country, especially one of the advanced industrial countries, to seek a competitive position in aerospace. Composites, considered high-tech items, play an important role in achieving a competitive edge in aerospace. The contraction of the U.S. and the world's economy is driving all segments of

manufacturing to greater levels of quality at *reduced cost*; therefore, this study is very timely. The ripple of this contraction is now affecting the Japanese economy as well, with losses and layoffs being reported for the first time since World War II. The aerospace industry can be compared to the automotive industry in the race to achieve greater affordability. Airlines, as well as governments, are focusing on cost. Initial cost is only a part of the equation as the emphasis is shifting to life cycle costs and product disposal costs.

It is apparent that the U.S. cannot afford to duplicate applied research between U.S. companies; international cooperation may be required as well. To increase the use of composites in a declining market will require broader applications which are only limited by dollars per fabricated pound.

In the overall scheme of advanced polymer composite structures manufacturing, the aerospace segment occupies a unique position. Unlike automobiles and electronics products, aircraft are still considered handmade products; this is especially true for aircraft composite structures. Therefore, the product price per pound is very high. Finished military high performance weapon system costs are nearly $1,000 per pound, and composite airframe parts range from $400 to $700 per pound. Composite parts range from $200 to $400 per pound despite today's low fuel prices.

Another unique aspect of the aerospace industry is low production rates. High value and low rates have produced some unique manufacturing methods which have precipitated high labor content operations. The very large non-recurring cost required to introduce composites is a significant issue and a major drawback in both military and commercial applications. Military aircraft manufacturers are faced with more starts and less production. Currently, commercial aircraft must be produced in quantities of 300 to 400 units to recoup the non-recurring costs.

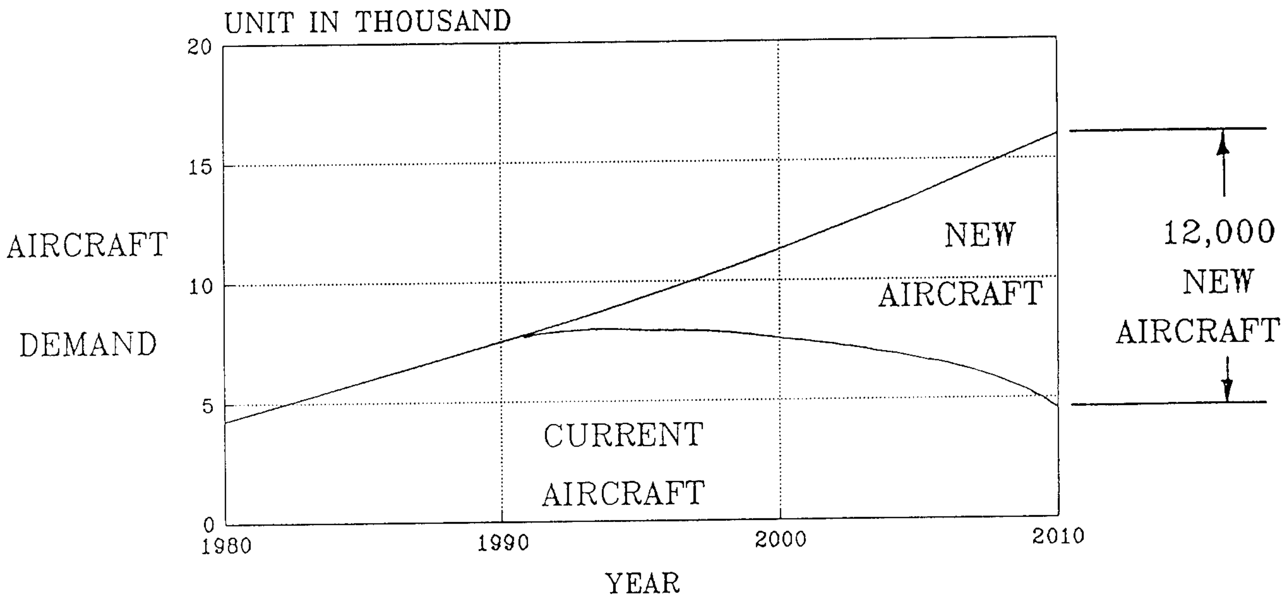
Many government-sponsored research programs and internal company research projects have been directed at low-cost composites manufacturing. To date, few have become production-qualified. The failures far outweigh the successes, and have yielded a loss of confidence. The military's successful implementations have been accompanied by high labor content and little automation, due to an unwillingness to compromise performance. In commercial applications, the low fuel prices have outweighed the advantages offered by light weight composites.

Yesterday's emphasis on weight savings has been replaced by an emphasis on cost savings and affordability. The cost of manufacturing aircraft parts is a major portion of the total cost; consequently, it is considered an area of potential cost savings. It is timely and relevant, therefore, to evaluate manufacturing technologies in the U.S. and in Japan, both of which are known as technologically advanced countries.

CURRENT EVENTS AFFECTING ADVANCED COMPOSITES MANUFACTURING TECHNOLOGY

Drastic cutbacks in defense spending due to the end of the cold war are painfully affecting many U.S. and Japanese aerospace companies. According to MITI (Ministry of International Trade and Industry), reliance on defense spending is much greater for the Japanese aerospace industry (75% military), than it is in the U.S. aerospace industry (56% military). This situation has been further aggravated by the deep and long recession in the United States, Japan, and other parts of the world. This economic recession is causing an unprecedented slump for the world airline industry, which has resulted in a record loss of $5 billion in 1992. However, a favorable long term outlook for the commercial aircraft business has offered a glimmer of hope to an otherwise gloomy picture for the aerospace industry.

The increase in world demand for commercial aircraft is a direct result of economic globalization and the increased reliance on air travel. Historically, the increase in world demand for commercial aircraft has been shown to match essentially the increase in GDP (gross domestic product) for the world; this means that an increase of 5 to 6 percent per year can be expected until the year 2010. Demand will be further enhanced by the problem of aging aircraft and the need to replace old airplanes. A market for 12,000 new aircraft worth $900 billion by the year 2010 has been predicted (Fig. 2.1). One third of the total number of new aircraft are to replace aging aircraft. Over the years, there have been many ups and downs in the demand for new aircraft, but the general trend has been upward. Fortunately, the upward trend is expected to continue. Composites usage in future aircraft will also continue to move upward. However, unlike in military aircraft, the problem of cost, particularly manufacturing cost, must be overcome. The technology already exists to incorporate small composite primary structures (e.g., horizontal and vertical stabilizers) into large commercial transport, but it does not yet exist for the incorporation of major composite primary structures such as wings and fuselages. The current drive is to develop the technology necessary to incorporate composites wings and fuselages into large commercial transport by the end of this century. For this to happen, it is essential that the cost of composite wings and fuselages be low enough to be an attractive option. This means that manufacturing cost as well as direct operating cost (DOC) must be equal to or less than that of metal primary structures. Unlike in military aircraft applications, it is acceptable to sacrifice a certain amount of performance in order to gain respectable cost savings. Although the development of a high speed commercial transport is still at an early stage, demand for low cost manufacturing will remain the same. Future competition will not be as much for improved performance as for reduced cost in materials and manufacturing.



- 1/3 TO REPLACE AGING AIRCRAFT
- 2/3 FOR FUTURE GROWTH
- $900 BILLION MARKET

Figure 2.1. Commercial Aircraft Demand by the Year 2010

Improved performance for military aircraft is still a high priority. However, the extremely high cost of today's military aircraft cannot be tolerated even by the military. The U.S. government is likely to continue eliminating or reducing the scope of its expensive aircraft programs. A few good examples are the A-12, B-1, B-2, ATF, and C-17 programs. The Japanese military programs cannot escape similar treatment from the Japanese government. The U.S. military agencies (USAF and Navy alike) as well as the Japanese Defense Agency (JDA), are now under pressure to reduce costs the same way the commercial aircraft builders do. It is not too difficult to see that future major military aircraft programs will be few and far between. Consequently, the pressure is on the defense contractors to find commercial programs to compensate for the potential loss in military work. This means military contractors must now compete directly with Boeing and Douglas in the United States, and with foreign commercial aircraft manufacturers globally.

Competing for more commercial work is particularly severe for the Japanese aircraft industry because of its very high reliance on its military budget (see Table 2.1).

To fully understand how composites technology stands within the Japanese aerospace industry, it is important first to understand the Japanese aerospace industry itself. The Japanese aerospace industry is relatively small compared to that of the U.S. and other industrial nations. It is only one-tenth the size of the U.S. aerospace industry, one-third the size of those of the U.K. and France, and about the same size as that of Canada. The export/import ratios for aerospace-related products of the major industrial nations are given in Table 2.2.

Table 2.1
Japanese Military/Civil Demand
(¥ billion)

YEAR	TOTAL OUTPUT (A)	GROWTH RATE	MILITARY (B)	CIVIL	RATIO (B/A)
1988	661	1.2%	523	138	79.1%
1989	731	10.6%	558	173	76.3%
1990	802	9.7%	601	201	74.9%
1991	851	6.2%	639	212	75.1%
1992	800	(6.0%)	N/A	N/A	N/A

Table 2.2
Export/Import Ratios for Aerospace Related Products

USA	JAPAN	FRANCE	U.K.	CANADA
3.3/1	1/6	2.5/1	1.28/1	1/1.5

The U.S. is the largest exporter and Japan is the largest importer (mostly from the U.S.) of aerospace related products. Although small, the Japanese aerospace industry has received acclaim for its advanced production technology, reliable delivery, and high quality. Its composite parts and components have also received similar acclaim.

The Japanese aerospace industry is unique in the sense that its aerospace-related sales account for only 20 percent of the total sales of the four major aerospace-related heavy industry companies. Sales percentages for a typical Japanese heavy industry company are shown in Figure 2.2. Diversification is the norm for the heavy industry companies, and it is rooted in the historical development of these heavy industries in general, and the Japanese aircraft industry in particular.

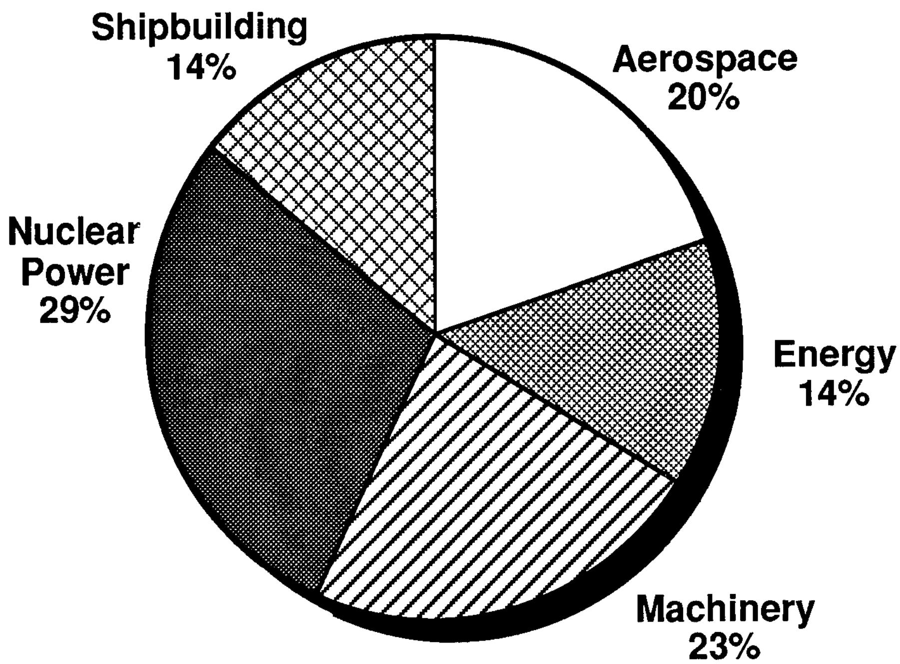


Figure 2.2. Typical Japanese "Heavy Industries" Company

U.S. companies are now racing to shift from military to commercial applications, with an emphasis on cost-cutting. This shift was started by NASA several years ago when it sponsored the ACT (Advanced Composites Technology) program. As expected, Boeing and Douglas (the only major commercial aircraft builders in the United States) received the largest share of the funding. The underlying theme of the ACT program is low cost technology and affordability.

REVIEW OF AEROSPACE APPLICATIONS

Application of advanced composites to aerospace can be divided into four categories: (1) aircraft, (2) rotorcraft, (3) spacecraft/missiles, and (4)

engines/nacelle. Within each category a further division is possible. For example, aircraft can be divided into combat aircraft, large transport, and small aircraft, and further divided into military and commercial applications. The design and manufacturing technology is different for each of the above categories; the difference is largely dependent upon the requirements set forth by each category. A brief description of the requirements and constraints of each category is delineated below to help explain the impact on the design and manufacturing technology:

Aircraft

Combat. This application requires high performance (weight, strength, stiffness are critical) and tolerance of severe environments. It involves moderate production rates and moderate durability. Many complex structures are required, resulting in high cost ($600 - $800 per pound of finished structure).

An automatic tape layup (ATL) machine is currently used for manufacturing large, somewhat flat structures, such as skins. An automatic cutting machine (ACM) is used to cut plies and fabrics for hand layup. Most of the complex and small parts are made by labor intensive hand layup.

Large Military Transport and Bomber. This application involves moderate to high performance in moderate to severe environments. Moderate production rates are typical and moderate to long durability is required. A mixture of large and small structures with both simple and complex shapes is fabricated for this application. The result is relatively high cost ($400 - $700 per pound of finished structure).

ATL is currently used for manufacturing large structures. ACM is used to cut plies and fabrics for hand layup. Most of the complex and small parts are made by labor-intensive hand layup.

Commercial Transport. This application involves moderate performance in moderate environments. Higher production rates are typical. Long-term durability is a requirement. The cost of certification is high. It entails the fabrication of a mixture of large and small structures with simple and moderately complex shapes. There is a high demand for low cost ($250 - $400 per pound of finished structure). Safety is a paramount consideration. Conservative approaches are typical due to the financial risks involved.

ATL is currently used for large structures in this application. ACM is used to cut plies and fabrics. Some filament winding is used, as is braiding for ducts and pultrusion for simple and long structures. The industry is still relying heavily on labor-intensive hand layup.

Small Transport and General Aviation. This is a relatively low performance application, in a less severe environment. Moderate to low production rates are typical. Short to medium durability is required. Certification cost is lower relative to the large transport category. Except for the wings and fuselage, small, less complex structures are involved for all-composite aircraft. Low cost is a must ($50 - $200 per pound of finished structure).

Mostly hand layup is used in current manufacturing practice. ATL and ACM are used for some applications. Filament winding is used for some structures. No fancy tooling or manufacturing techniques are employed.

Rotorcraft

Military. This is a high performance application. Weight, strength, stiffness, and durability are critical. Operating environments are severe. Production rates are low to moderate. Battle damage tolerance is important. There is a high usage of composites (e.g., in rotor blades, tail blades, fuselages, and booms). Cost is relatively high ($500 - $700 per pound).

Hand layup is used for rotor and tail blade manufacturing. ATL and ACM are used for fuselage and boom. There are some filament winding applications.

Commercial and General Aviation. These aircraft require low to moderate performance, and usually operate in moderate environments. Production rates are low to moderate. In this industry, there is a high usage of composites for rotor blades, tail blades, bodies, and booms. Moderate cost ($200 - $350 per pound) is typical.

Hand layup is currently used for rotor and tail blade manufacturing. ATL and ACM are used for some body and boom structures. There are some filament winding applications.

Spacecraft and Missiles

This is a high to ultra-high performance area. Weight, strength and stiffness are extremely critical. There are numerous special and unique requirements. These vehicles operate in severe to extremely severe environments. Very low production rates are typical for some spacecraft (e.g., satellites) but high for some others (e.g., small missiles). There is essentially no durability requirement -- it is a "one shot" deal. Extremely high costs ($1,000 to over $10,000 per pound) are typical.

Current manufacturing techniques require the use of high precision hand layup with extremely complex tooling. Precision filament winding is used for circular shapes.

Because of low production rates, labor-intensive hand layup is the main manufacturing technique.

Engine/Nacelle

There are uniquely high performance requirements for this application. These parts operate in severe environments. There is a high demand for durability. For fan blades, there is an acoustic environment issue, and net shape and complex contour are requirements. Relatively high production rates are a feature. Engine blades are expensive, whereas nacelles are produced at moderate cost ($770/lb finished in an automated process for blades, and $350 - $450 per pound for nacelles).

Precision hand layup is required currently for blade manufacturing. Tow placement is also used for this application. A combination of filament winding and hand layup is used for nacelles. Honeycomb construction is used for acoustic sound absorption in nacelles. Precision co-curing techniques are used for cascades.

INTERNATIONAL COOPERATION IN THE AEROSPACE INDUSTRY

There is no other industry more international than commercial aircraft, and the trend toward further internationalization is increasing. The primary reason for this trend is the enormous cost of development. One company, or even one country, cannot cope with the risk and the cost of developing a new commercial transport. Another factor contributing to internationalization is "off-set" deals made between aircraft manufacturers and countries with airlines buying airplanes worth billions of dollars. Internationalization is affecting composite technologies directly and indirectly. Currently many Japanese aircraft manufacturers are producing composite parts and components for Boeing and Douglas.

In 1986 a revision was made to the Japanese Aircraft Industry Promotion Law. The revision stipulates that the Japanese government can provide development support for aircraft *only* in the case of international cooperative development projects. The law provides two justifications for international cooperation:

1. Cooperative international development is necessary because of the great risk involved in aircraft development.

2. A primary goal of Japanese policy is to encourage international exchanges of technology.

Currently, there are two major programs in which the Japanese aircraft consortium is taking part. They are the Boeing B-777 (21% share) and the IAE V-2500 engine

(23% share). MITI has already announced plans for future international cooperative programs:

1. YXX 150-seat medium size transport
2. YSX 50-100 seat small to medium size transport
3. High Speed Civil Transport (HSCT)
4. Ultra Large Aircraft (Super Jumbo)
5. Engine Development for HSCT

In addition to the Japanese government, Japanese aerospace companies also realize the importance of international cooperation and collaboration. Some Japanese companies report that their manufacturing technologies have already been transferred or are being transferred to several American companies, notably MHI's sophisticated large structure co-cure technology to General Dynamics (now Lockheed). It is expected that technological transfers from Japan to the U.S. will continue in the coming years. However, the success of these transfers will be highly dependent upon human factors, e.g., the willingness of U.S. companies, particularly their upper management, to accept the technology.

CHAPTER 3

AUTOMOTIVE AND INDUSTRIAL APPLICATIONS

Joseph S. McDermott

AUTOMOTIVE

Overview

Despite the potential benefits of lighter weight and durability resulting from corrosion resistance, advanced composites are not recognized as a material of choice in the near term for automotive applications. Significant changes on a broad spectrum would be required to make advanced composites attractive for widespread commercial use in cars and trucks. The principal barrier is the high cost of the raw and converted materials when compared to existing options, and the perception that even with volume production in yet-to-be-perfected processing methods, the costs would still be too high.

The general economic assessment has stalled research on significant immediate requirements, such as the design and engineering data base which would enable producers to employ advanced composites with acceptable risk, and the development of the processing technologies which would permit manufacture of components in the tens of thousands of units per year.

Nevertheless there are opportunities for advanced composites in specific components in the commercial automotive sector. In specialty vehicles of several types, produced in small numbers appropriate to manufacturing rates for advanced composites, these materials have an opportunity to demonstrate their performance benefits, apart from the requirements of the competitive marketplace.

Context

The world automotive market is dominated by three major manufacturers in North America, a so-called "Big Five" in Japan, and a slightly more fragmented market in Europe, where producers are less dominant in market share but formidable in their technologies. The business is global, rapidly changing, a significant source of horizontal and vertical employment, and intensely competitive. Management must continually balance the demand to invest in research and development in numerous technologies in order to appeal to consumers and respond to competition, with the demand to be the efficient, low-cost producer.

At the time of this study, the benefits of advanced composites have not outweighed the expense of their development for widespread use.

Advanced manufacturing of what we may call *engineered* composites is, however, a different story. That is, the industry worldwide is investing in process improvements for the molding of polymer composites using forms of conventional E-glass in mid-level performance resins, both thermoplastic and thermoset. Although these materials do not meet the definition set out in the scope of this study, a thorough assessment seems to require mention of these advances in manufacturing. In the long term, these may lead to evolutionary development of advanced composites applications for the commercial market.

Applications

Pultruded Driveshafts. The first high-volume, true automotive application of aerospace technology is the driveshaft developed by the Spicer U-Joint Division of Dana Corporation. Following an earlier driveshaft introduction on 1985 Ford Econoline van models, the Spicer product on General Motors pickup trucks enjoyed a demand three times that of projected sales in its first year (1988). At approximately one pound of carbon fiber per unit, 250,000 lbs. of carbon fiber were consumed by this application in 1988. Volume has continued to grow well in excess of light truck growth rates during the 1988-92 period.

Despite the success of the technical and production aspects of the part, economics limit the growth of this application. Essentially, the graphite driveshaft is limited to longer-bodied truck vehicles, which require a two-piece shaft in steel. When the part length is less than 58 inches, a one-piece steel shaft is substantially less expensive than the one-piece composite unit. In the GMC truck potential of 500,000 units annually, the composite eliminates a multi-piece driveline, thus reducing assembly time, inventory cost, maintenance, and part number complexity. In addition, the composite assembly is 60% lighter than its two-piece predecessor, delivering a 20-lb. weight saving per vehicle, offering better fuel economy and mileage. Other benefits are the elimination of warranty associated with center

bearings, noise and vibration dampening in the passenger compartment, corrosion-resistance, and custom design of driveshaft performance based on model use and power train system.

Production begins with a seamless aluminum tube. A proprietary vinyl ester resin, with both glass and graphite continuous fiber, is then pultruded over the tube in pultrusion equipment purpose-designed by the Morrison Molded Fiber Glass Company (MMFG) -- formerly a unit of Shell Oil Company (now an independent company), Bristol, VA. It is the composite formulation which is responsible for eliminating the center bearings. The part is engineered with an isolation barrier between the tube, and graphite fiber eliminates electrolytic galvanic corrosion.

Production rate and economics for the Spicer unit are not available. In 1985, competitors estimated that full production would demand one unit, or five to six feet per minute. A mid-1980s study by a filament-winding manufacturer, however, revealed interesting cost analyses: contemplating a unit three and one-half inches in diameter, 60 inches long, capable of 5,000 RPM, 2,500 lb.-ft. ultimate torsion load, and a volume of 100,000 driveshafts per year, a 24% reduction in carbon fiber price would lower the cost of the assembly by only 2%. Assuming carbon fiber at $17/lb., and epoxy resin to meet boil and ultimate torque tests, the materials bill was $6.57. Completing analyses, with slightly different dimensions and some variation in materials, gave total part cost at $60 to $133 per unit.

The panel learned in an interview with a planning official of Toyota that the company has licensed driveshaft technology from a European unit of the Spicer/Dana organization. But the company has no plans to introduce the advanced composite driveshaft in production models.

RTM Panel. A second advanced composite production component, although at a low volume, is the structural panel which covers the torsion box running between the two seats of the Dodge Viper. Called the "Top-of-Tunnel" or "T-o-T," it is molded by resin transfer by Dow-United Technologies Composite Products, Inc. This component consists of skins of $\pm 45°$ woven graphite fabric, and a core of continuous strand fiberglass mat. The advanced composites part of 3.1 lbs. replaced a steel part with an estimated weight of 10 pounds.

The Viper model appeared as a prototype at the January 1989 auto shows. Introduction of the model by the first quarter of 1992 was considered an innovation by Detroit. In some respects it was Chrysler's answer to the GM Corvette; the entire 1992 production run of 300 units was sold out within one month. Five thousand units are to be produced in 1993. The body skin consists of 35 fiberglass/acrylic panels molded by two conventional RTM suppliers, although the hood will be converted to SMC when full production levels are reached.

Fiber Glass/Epoxy Springs for Heavy Trucks and Trailers. Fiber glass/epoxy springs for heavy trucks and trailers became commercial in the U.S. in 1992, after several years of lab and over-the-road testing. The Delco Chassis Division of General Motors in Dayton, Ohio molds the single-leaf springs with unidirectional fiber glass in a specially-formulated epoxy. The design, materials, and process are similar to those for the original "Liteflex" spring introduced on the 1981 Corvette. The big difference, of course, is size. A fiberglass/epoxy spring for heavy-duty trucks and trailers is 3.5 feet long and 3 inches thick, but weighs only 22 pounds - about one-third as much as steel.

The absence of comparable manufacturing and use in Japan was attributed by a research source in Tokyo to different demands from the domestic truck market. Since the benefits for such parts in the Japanese market are not great, the exhaustive testing and evaluation in advance of use have not been undertaken.

Rocker arm covers, suspension arms, wheels, and engine shrouds are examples of automotive applications which have been prototyped with ACM. But design refinements such as precise fiber orientation, or the use of integral ribs, have shown that E-glass composites in lower cost resins can be used to make these articles more cost-effectively.

Filament-Wound Fuel Tanks. A European pioneer in all-composite compressed natural gas (CNG) cylinders put its first units in service in 1989. These were thermoplastic-lined units, with carbon fiber/epoxy overwrap. Since that time international developments have proceeded, with at least a dozen major composites entities contributing to development of the technology and toward the adoption of International Standards Institute specifications. No consensus has been reached on material combinations. In addition to the advanced fibers and resins within the scope of this report, steel, aluminum, and E-glass are still contenders for various elements of a viable CNG cylinder. This report does not discuss the numerous production, size, weight, performance, and cost issues which are affecting fuel tank research at this time.

Several companies in North America are in commercial production of at least partially-advanced composite CNG tanks in the hundreds of units for municipal bus and utility truck contracts. World-wide, there are half a million to 800,000 such tanks on the road, according to the International Association for Natural Gas Vehicles.

Although a U.S. Department of Transportation standard exists to support this use of composites, the American National Standards Institute (ANSI) draft standard and the ISO document do not fully accommodate all-polymeric composite material systems.

Electrical Vehicle Body Components and Assembly Units. Electrical vehicle body components and assembly units such as battery trays would appear to be suitable

uses for advanced composites. The lightest possible weight is desirable in this application. Yet strength-to-weight ratio is not an exclusive concern. Cost and proven manufacturability also influence materials selection decisively. Advanced composites would seem to have a role only when high specific strength is required for a specialized function.

The cost-driven reality of even the experimental applications was evident in a visit to research facilities of Mitsubishi Kasei.

This pre-eminent supplier had no automotive advanced composites to discuss, but did offer an excellent example of advanced *process* development with transportation applications.

In cooperation with funding from an environmental group and an electric utility, Mitsubishi Kasei has perfected the conceptual elements for one-shot molding of the entire body and platform for an electric motor scooter. Candidate resin materials for this application would be polyurea, an epoxy-polyurethane blend, or other thermosets suitable for reaction-injection molding (RIM). The reinforcement would be conventional E-glass, unless it were determined later in commercial development that "patches" of higher-performance reinforcements were required at points of exceptional stress on the frame. The accomplishment demonstrated by this program is the feasibility of molding a very complex structural part, in only several minutes cycle time, using only a single resin injection port, and without preform "drift" within the mold.

While this project showed world-class development capability, it cannot be said that the RIM process demonstrated is advanced beyond the research work published by Ford Motor Company in cooperation with Dow Chemical, relative to structural cross-members for automotive use, or beyond the research on bumper beam assemblies that has been completed by the U.S. Automotive Composites Consortium. Like the latter, the Mitsubishi Kasei technology has produced parts which meet apparent physical performance requirements, but the scooter bodies have not been put into commercial production.

Aftermarket and Specialty Components

A number of uses for advanced composites in the automotive sector are being developed for modular or stand-alone components which could be retro-fitted to existing vehicles (an example is tanks for compressed natural gas [CNG] as an alternative fuel). Other applications which should be noticed are specialty parts for prototype transportation whose commercial future is uncertain (examples in this category are components for electric vehicle bodies).

Automotive Conclusion

The relative absence of advanced composites from the Japanese automotive scene does not indicate disinterest in advanced technologies for cars generally. At one of the "heavy industry" interviews, the panel was shown visuals of aluminum honeycomb-core panels stamped for use as monolithic, configured floor pans for conventional passenger cars. The host research team said this structural part is in production for a low-volume model which is having a very good reception in the domestic market.

INDUSTRIAL

Overview

By industrial, we mean machinery, or equipment and structures used by industry, as contrasted with consumer goods, which are not auto, aircraft, marine construction, or some other familiar end-use category. This is the most fragmented market that we studied.

The literature and those we interviewed show evidence of selective use in Japan, as in the US, of pultruded or filament-wound rollers for printing and packaging, in the textile industry, and in high-speed plastic boat manufacturing. That is, selective use where the combination of do-ability, resistance to chemicals, the need for light weight -- a whole range or combination of performance requirements -- made these kinds of expensive parts cost-efficient. There is no discernible competitive advantage for the U.S. or Japan in either the research, or the production, or the use of this type of component -- again, not speaking of glass-reinforced materials here, but of carbon fiber and aramid units in an engineered resin.

In other industrial products, for example in robot arms, certainly there is more widespread use of advanced composites as a component in that kind of equipment simply because the Japanese have a far bigger robot industry. In machine tool components, another usage, we found the same kind of uses made very selectively for advanced composites.

On the other hand, in the area of thermoplastics reinforced with glass fiber, typically injection molded, these are in widespread use in North America because we have far more applications, in business equipment, appliances, a limited number of commercial consumer goods. We did not see as much of that in Japan although the technology is no mystery, and again, if there were markets of opportunity we would expect the evaluation of technology in this to be about the same.

A large characteristic in this industrial area is the fact that we felt we didn't have much access to what truly may be going on, because this type of product isn't highly promotable. It doesn't have great surface-finish characteristics, something useful in a press release or an annual report, and -- just as here -- we felt our hosts discerned competitive advantage with their competitors in Japan. And they felt perhaps some reluctance, just as we would, to publicize a use of advanced composites in the internals of a machine or in some production activity that was going to create a market for someone else. One other application is of considerable interest in North America -- composite tanks for liquid natural gas for alternative fuel vehicles. There has been a setback in the standards being set for certain uses by DOT that virtually amounts to a materials specification adverse to composites, in the market governed by that standard. If that's the case, there's a mirror-image situation in Japan. We found that the pressure vessel manufacturers -- those who make racked bottles for fire service, mountain climbing and so on -- who invested three years ago in the development of these types of tanks for land transportation equipment have slowed down and discovered that there are some glitches, at least for the time being, in the adaptation of advanced composites for that market.

In summary, automotive and industrial applications in Japan were much more difficult to uncover than was the case for aerospace applications. The JTEC panel concluded that there is a rough parity between Japan and the United States in this area.

CHAPTER 4

APPLICATIONS OF COMPOSITES IN CIVIL ENGINEERING

V. M. Karbhari

SCOPE OF THE STUDY

It is essential that this chapter be prefaced with the note that the subject of this chapter was initially not considered as being of sufficient importance to warrant a separate chapter in the report. However, it turned out to be the important point of difference between new developments in the U.S. and those in Japan. Although it was known to some in the panel that the Japanese composites community had been making strong overtures to the civil engineering area over the past five years, the magnitude of their commitment to this new and emerging market was simply not comprehended. This chapter thus is intended to only briefly touch upon the subject, as a full and comprehensive treatment would be beyond the scope of the present report. This should, however, be in no way construed to suggest that the study did not unearth a large body of useful information; rather the amount was so large that it was viewed as being overwhelming for the overall report.

INTRODUCTION

Before beginning a brief description of Japanese activities in the civil engineering area, it is worthwhile to list the reasons behind the rapid development and growth of this area in Japan, where despite efforts by U.S. companies such as DuPont, Hercules and Dow over the past decade, very little real advance (in terms of market penetration) has been seen in the U.S.

1. A shortage of skilled labor combined with an aging workforce

   This presents a special challenge to Japanese construction firms in retaining their global position. Simplified construction methods, resulting from the use of lighter materials that are easier to handle and can be largely prefabricated, are major drivers pushing the use of composites.

2. Societal preoccupance with neatness and aesthetics

   The potential of having cleaner work sites while simultaneously increasing the capability of integrating form and function with aesthetics makes the use of composites and advanced materials attractive.

3. The predominance of a marine environment

   Japan's major urban and industrial centers are all within a marine environment that makes corrosion of steel a constant problem. The constant deterioration of steel and even wooden structures provides a strong impetus for the use of corrosion- and degradation-resistant materials.

4. Growth in population and the corresponding increased demand on transportation and related infrastructure

   Infrastructure in Japan has been overwhelmed by a level of usage not foreseen. In addition to previous poor design and construction practices that resulted in accelerated deterioration, lack of large spaces for expansion has led to the search for innovative solutions.

5. Earthquakes and seismic activity

   The need for lighter construction materials and more seismic resistant structures has placed high emphasis on the use of new and advanced materials that can not only decrease dead weight but can also absorb the shock and vibration through tailored microstructures. Similar objectives are seen for retrofit/rehabilitation/strengthening of pre-existing structures that have to be retrofitted to make them seismic resistant, or to repair damage caused by seismic activity.

6. Close link between materials suppliers and construction industry

   A major barrier to the acceptance of composites by the construction industry in the U.S. is the lack of connection between the materials suppliers and construction industry at a level higher than salesman/potential customer. The *keiretsu* structure has already forged strong business links between these

groups in Japan, whereby each has the potential for using the other as a demonstration of capabilities or as a quick and ready resource center.

7. Research and development laboratories in the civil construction area

Whereas large construction companies in the U.S. have no R&D centers, there are as many as 15 such centers in Japan -- funded and managed by individual companies. Thus the search for and the development of new and improved materials begins with the company rather than from the outside, thereby increasing its acceptance.

8. Codes and regulations

A significant difference between procedures in the U.S. and Japan is that the construction industry is far less curtailed by codes and regulations in Japan than it is in the U.S. The flexibility afforded to them in experimenting with new materials and structural forms is higher. This in no way should be taken to mean that they are any less responsible or liable than their U.S. counterparts; rather, Japanese companies feel individually responsible for the structures they build. However, it is much easier for them to build without completely qualifying the materials of construction as long as viability has been proven. The time taken to get through the bureaucracy is also often much less.

9. Positioning and global competitiveness

Japanese construction companies and the materials industry were quick to realize that the reduction in defense spending would lead to enormous opportunities for application of composites in the infrastructure area, and began to commit their resources at an early date, so as to gain a competitive edge. The competitive position of Japanese construction companies in the international arena (especially in the Middle East) has also made it possible for them to initiate the use of new materials earlier (such as the use of carbon fiber reinforced concrete in the Al-Shaheed monument in Iraq by Kajima Corporation).

10. The critical need to find a use for carbon fiber

Although carbon fiber is produced worldwide, Japanese companies have been more aggressive not only in finding new markets, but also in trying to develop them (the use of the *keiretsu* and more advantageous code regulations no doubt are factors as well). This may in part be due to the higher overall carbon fiber production capacities in Japan as compared with those in the U.S.

11. Willingness to establish demonstration sites

    Materials suppliers in Japan appear to be more willing to use their own structures as demonstration sites for their products (Shimizu through the use of NEFMAC in their building, Mitsubishi Kasei and Tonen Corporation through the use of carbon fiber for rehabilitation, etc.) than their U.S. counterparts. Part of this is no doubt due to codes, but a large part is in essence their willingness to make major investments towards long term goals, rather than being tied to quarterly earnings (as in the U.S.).

This chapter discusses the use of advanced composites in Japan in grid-type structures. Other uses, including short and continuous fiber, cable-typed elements, 3-D and grid structures, and applications in retrofit and rehabilitation will be covered in future publications by this author. This was found to be the best way to maintain the original focus of this study, which was composites in general and not just civil infrastructure applications. The development of the civil engineering market will also be discussed. It should, however, be noted that the cost-competitiveness of the products compared to traditional construction material is based on claims that the panel did not attempt to check, and hence should be treated with a degree of caution. However, it is clear that the Japanese are far ahead of the U.S. in the development (and in the capturing) of this new market and are steadily increasing their lead.

Rather than present a detailed list of the motivation and background for the use of composites in infrastructure, the interested reader is referred to Karbhari (1993) and Ballinger (1992). In the context of this report, we discuss pertinent developments in the area of grid-type structures.

GRID-TYPE STRUCTURES

Although a majority of developments in the area of composite reinforcement for concrete have focused on the investigation of composite rebar, it must be stressed that the specific form is not the best application of composites, due to reasons related to bond development. In this section, we describe a representative 2-D grid structure called NEFMAC (New Fiber Composite Material for Advanced Concrete) as shown in Figure 4.1.

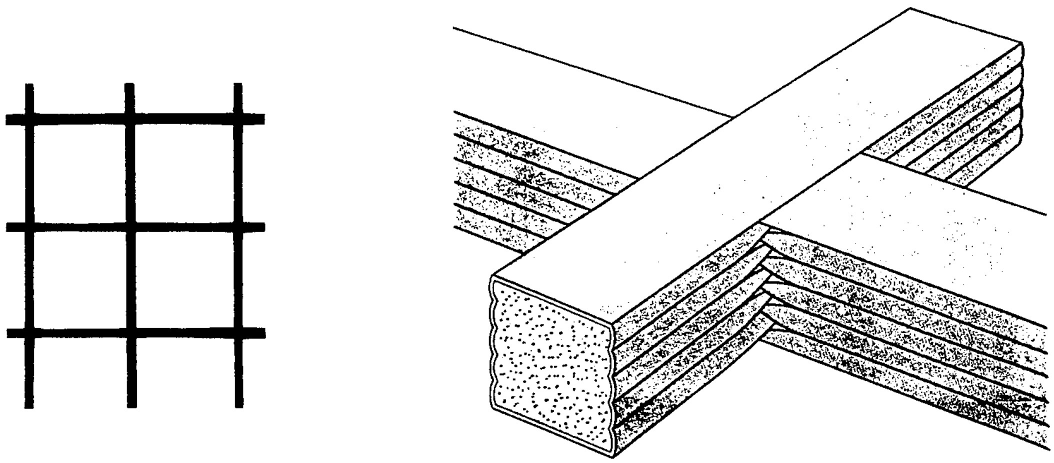


Figure 4.1. Schematic of NEFMAC Grid

NEFMAC is a grid-type reinforcement for concrete structures. It consists of high-performance fibers such as glass, carbon, aramid, and hybrids, impregnated with resin systems ranging from vinylesters and other thermosetting resin systems to thermoplastics. Besides the inherent corrosion resistance, the grid form itself is advantageous in that the intersections provide anchorage and mechanical interlock in the concrete, facilitating good stress transfer. Again, due to the non-corrosive and alkali resistant (based on resin selection) nature of the grid, cover requirements are reduced, resulting in lighter slabs and other concrete elements. A listing of applications is given at the end of this section.

NEFMAC is produced by the NEFCOM corporation -- a cooperative venture between Shimizu Corporation and Asahi Glass Matex Company (formerly Dainihon Glass Industrial Company). The actual method of production is shown in the schematic in Figure 4.2, and is termed "pin winding." The process is similar to filament winding in that individual fibers/tows are placed in prespecified patterns after being impregnated in a wet-bath. The process is a semi-batch type operation, unlike the continuous operation of forming NESTEM geosynthetic material for soil reinforcement. In the NEFMAC process a series of continuous fibers are dispensed from individual creels by a mechanical system, through a wet-bath to be deposited by two orthogonal traveling (winding) heads. The heads are moved at synchronized speeds that define the size of the grid. Successive movement of the heads results in fiber cross-over and placement of interlocking layers until the desired content/cross-sectional area is achieved. The process is currently capable of line

speeds as high as 2 m/min in continuous mode, with about 200 m^2 of grid produced per hour. Cure is achieved through the use of either infra-red or ultraviolet heat sources assisted by peroxide catalysts in the resin system. Post-cure is conducted at room temperature. A list of primary characteristics and their resulting features is given in Table 4.1.

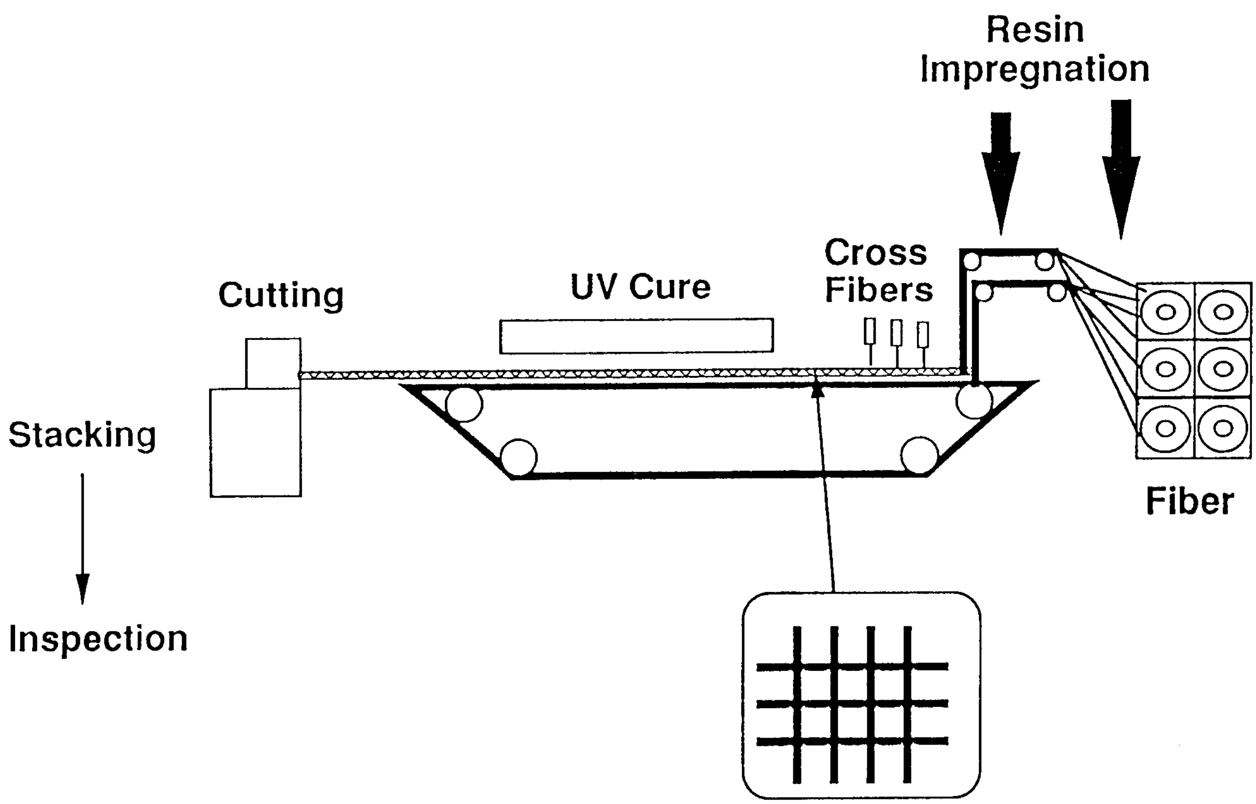


Figure 4.2. Schematic of the Pin-Winding Process

Four basic types of NEFMAC are available based on the type of fibers used. A comparison of gross properties is given in Table 4.2 and representative stress-strain profiles are shown in Figure 4.3. A wide variety of fiber types are used within these broad classes, the details of which are given in Table 4.3.

Table 4.1
Principal Characteristics of NEFMAC

CHARACTERISTICS	FEATURES/ADVANTAGES
Non-corrosive	Improved durability and needs less concrete cover resulting in lower thickness and weight
Excellent resistance to alkalis, acids, and chemicals	Depends largely on resin selection. Improved durability and ease of use in conditions where damage/deterioration by salt, chemicals or extremes of cold are expected.
Continuous fibers	Good performance attributes without local "wrinkling" as seen in pultruded rods. Easy fabrication of hybrids.
Non-magnetic	Electromagnetic transparency resulting in ease of use in hospital and for rooms where electromagnetic transparency is required.
Light-weight	Specific gravity of less than 2 - results in ease of transportation and placement. Also results in overall lighter structures.
Tailorability	Due to potential for hybrids and shaping, grids can be made to easily follow contours such as for tunnel linings.

Table 4.2
Main Types of NEFMAC Based on Reinforcement Type (Vinylester Resin Based)

TYPE	FIBER	SPECIFIC GRAVITY	TENSILE STRENGTH kg/mm^2	TENSILE MODULUS OF ELASTICITY kg/mm^2
A	Aramid	1.28	130	5,700
C	Carbon	1.42	120	10,000
G	Glass	1.70	60	3,000
H	Glass/Carbon Hybrid	1.65	53	3,700

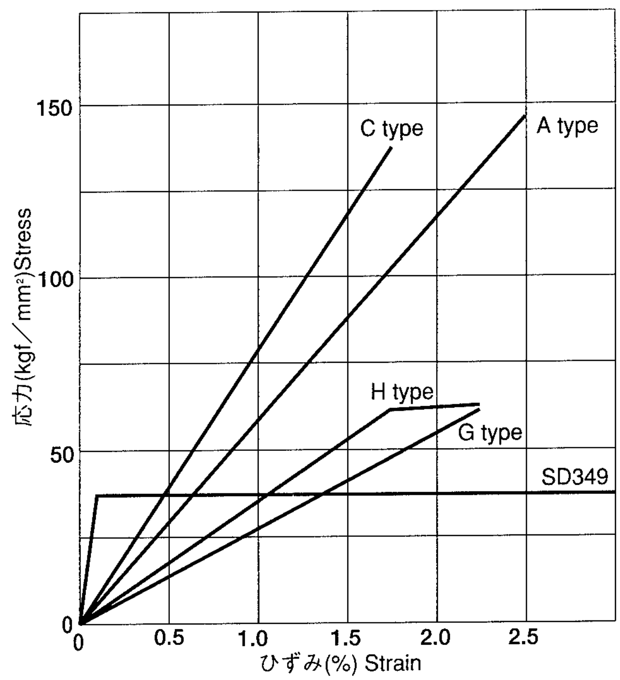


Figure 4.3. Typical Stress-Strain Profiles

It is interesting to note that the range is wide and includes fibers manufactured in Japan (Torayca - Toray Industries, Besfight - Toho Rayon Company, Technora - Teijin) and abroad (Kevlar 49 - DuPont). The hybrid, using a combination of glass and carbon, is designed to have a proportional limit and bi-linear stress-strain profile, similar to that of steel. Other hybrids such as high strength or high-modulus carbon and aramids are also available, based on specific needs. The size of a NEFMAC grid is given by specifying the area of the bars and the interval spacing. Figure 4.4 gives a detailed schematic of the grid with details of geometrical specifications.

The cross-sectional area varies from 32 - 3806 mm^2 for glass, carbon and aramid based NEFMAC grids, and from 284 - 3806 mm^2 for hybrid grids. Typical interval spacings are 25, 50, 75, 100 and 150 mm (nominally 1, 2, 3, 4 and 6 inches). Although the standard profiles are flat panel-type structures, L and curved profiles are also available, as are full 3-D cage type structures that include shear reinforcement. Standard specifications of the NEFMAC grid are given in Table 4.4.

Table 4.3
Details of Fiber Type

FIBER	DENSITY	TEXTURE	FIBER DIAMETER	TENSILE STRENGTH	YOUNG'S MODULUS	ELONGATION	REMARKS
	g/cm^3	g/1,000m	μ	kg/mm^2	kg/mm^2	%	
E-GLASS	2.54						
Monofilament				350	7,400	4.8	
Roving		2,220	22	200	7,400	2.8	2,300 filaments
T-GLASS	2.49						
Monofilament				475	8,600	5.5	
Roving		2,240					
CARBON							
High-strength (HS)	1.77	800	7	350	23,500	1.4	TORAYCA T300, 12,000 tows
	1.77	810	7	350	24,000	1.5	BESFIGHT HTA, 12,000 tows
	1.79	800	7	380	24,000	1.5	PYROFIL T-1, 10,000 tows
High-modulus (HM)	1.81	364	6.6	270	40,000	0.6	TORAYCA M040, 6,000 tows
	1.78	750	6.7	270	35,000	0.77	BESFIGHT HM-35, 12,000 tows
	1.85	900	8	280	36,500	0.7	PYROFIL M-1, 10,000 tows
ARAMID							
Kevlar 49	1.45	1,267	11.9	280	13,000	2.4	(11,400-denier* roving)
Technora (HM-50)	1.39	167	12	310	7,100	4.4	T-240, 1,500 deniers
STEEL							
SD-35	7.8			>50	21,000	>18	JIS G 3112
Stainless Steel	7.83			176	20,300	2.0	

* Denier = g/1,000m

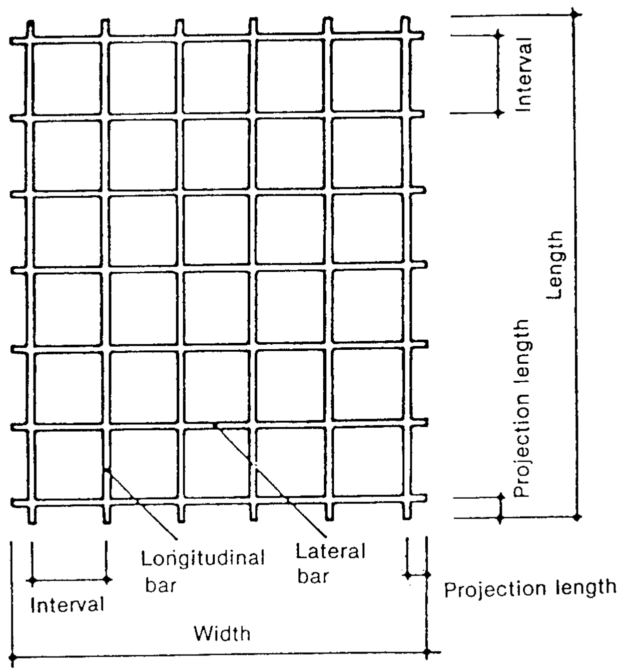


Figure 4.4. Geometrical Features of NEFMAC

Within the limits of this chapter we will briefly review the use of NEFMAC in three applications: (1) slabs, (2) shotcrete reinforcement in tunnels, and (3) 3-D reinforcement in beams.

Slabs

NEFMAC reinforcement has wide application in concrete slabs due to its corrosion and chemical resistance, its light weight, and its need for significantly less cover. A comparison of the behavior of the reinforcement types used in one study is shown in Table 4.5, and a schematic of the slab reinforcement is given in Figure 4.5.

Table 4.4
Standard Grid Specifications (Available Commercially)

FIBER TYPE	BAR NO.	SECTIONAL AREA (mm^2)	MAX. LOAD CAPACITY (tonf)	STANDARD WEIGHT (g/m)
Aramid	A6	16.2	2.1	21
	A10	36.2	4.7	46
	A13	60.0	7.8	77
	A16	92.3	12.0	118
	A19	136.0	17.7	174
Carbon	C6	17.5	2.1	25
	C10	39.2	4.7	56
	C13	65.0	7.8	92
	C16	100.0	12.0	142
	C19	148.0	17.7	210
	C22	195.0	23.4	277
Glass	G2	4.4	0.26	7.5
	G3	8.7	0.52	15
	G4	13.1	0.78	22
	G6	35.0	2.10	60
	G10	78.7	4.7	130
	G13	131.0	12.0	220
	G16	201.0	17.7	342
	G19	297.0		510
Carbon/Glass Hybrid	H6	39.5	2.1	65
	H10	88.8	4.7	147
	H13	148	7.8	244
	H16	223	12.0	368
	H19	335	17.7	553
	H22	444	23.4	733

Table 4.5
Comparison of Reinforcements

REINFORCEMENT	MAXIMUM LOAD (tons)	YOUNG'S MODULUS (kg/mm^2)	STRAIN AT MAX. LOAD (μm)
Glass Fiber in Vinylester	2.23	2,910	23,100
Glass/Carbon Hybrid in Unsaturated Polyester	2.09	4,990	14,900
Glass/Carbon Hybrid in Vinylester	2.22	4,590	14,800
Steel Mesh	1.80	18,100	15.1*

* = % Elongation

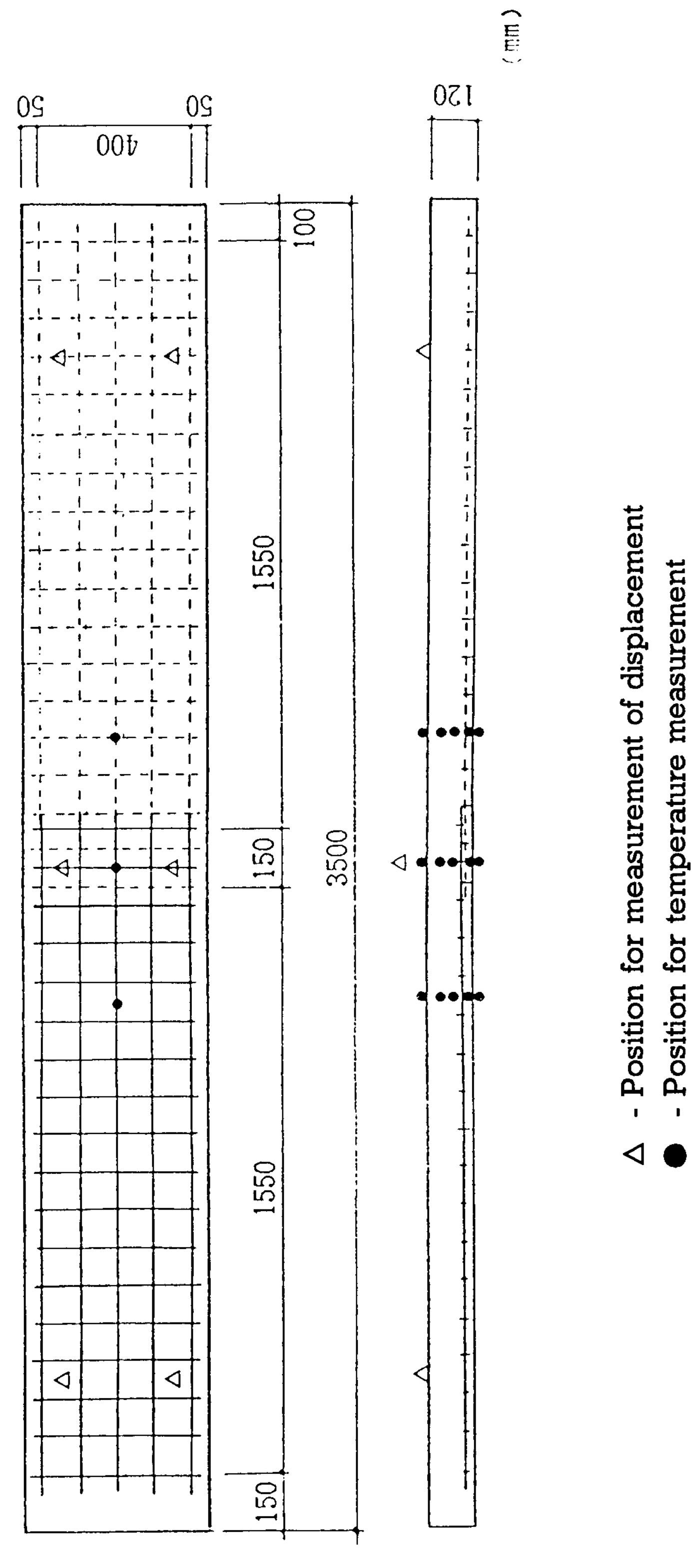


Figure 4.5. Details of the Test Slab

An overall comparison of behavior is given in Figure 4.6, which also shows the effect of temperature. It was concluded that deflections in NEFMAC were comparable to those with steel until 600°C, with almost no recognizable differences. The Japanese code for allowable deflection is also met by the NEFMAC grids at the one-hour fire resistant levels under specific design details.

Shotcrete Reinforcement in Tunnels

NEFMAC shows considerable potential for use as reinforcement of shotcrete in tunnels because of its corrosion and chemical resistance, its light weight, and its ease of forming to fit curvatures. A typical M-⌀ curve comparing NEFMAC reinforced and welded wire fabrics reinforced shotcrete panels is shown in Figure 4.7.

Since the reinforcing material is placed along the center plane in such applications and the reinforcement ratio is small, the maximum load coincides with cracking load, irrespective of the kind of reinforcement. NEFMAC would appear to be better because of the advantages stated earlier. Table 4.6 gives a listing of the applications of NEFMAC in shotcrete between May 1986 and June 1987. It is significant that no failures have been observed so far, and it should be noted that under some of the prevalent conditions, metallic reinforcement would have degraded due to corrosion and/or chemical attack resulting in overall failure/cracking of the structural element.

3-D Reinforcement in Beams

It is possible to create 3-D cages of NEFMAC that are analogous to the steel reinforcement cages comprised of longitudinal and shear reinforcement as in Figure 4.8.

Tests in fatigue have demonstrated that NEFMAC has a fatigue strength equal to or greater than that of a reinforcing steel bar.

Applications

NEFMAC is currently claimed to be effective for use in:

1. Tunnel supports and supports for storage containers
2. Airport facilities such as runways and aprons
3. Roads and bridge structures
4. Marine and offshore structures
5. Power plant facilities
6. Architectural features and structures such as exterior walls, handrails, etc.

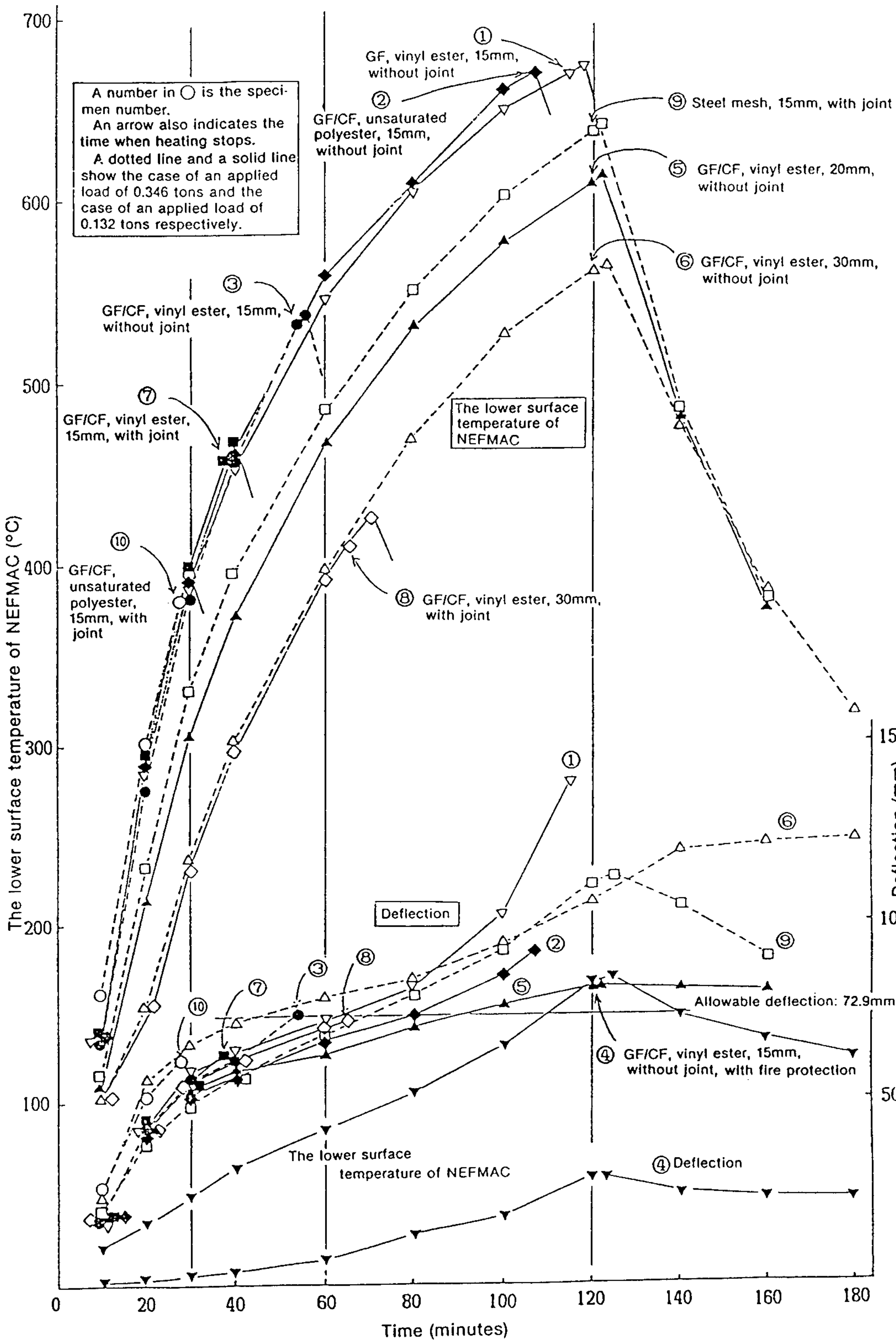


Figure 4.6. Stress/Strain Behavior of NEFMAC as a Function of Temperature/Time

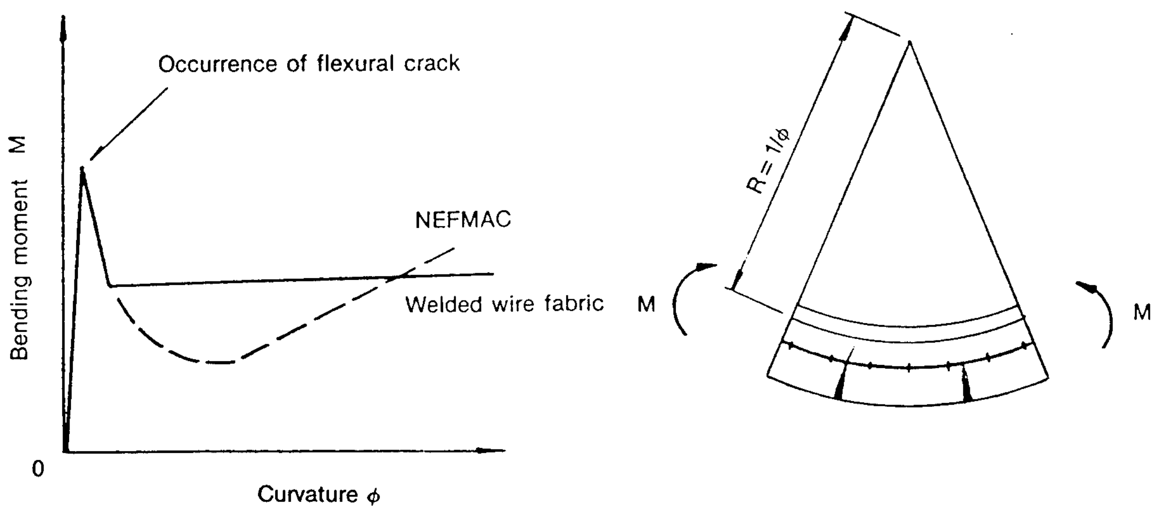


Figure 4.7. Comparison of M-ø Behavior

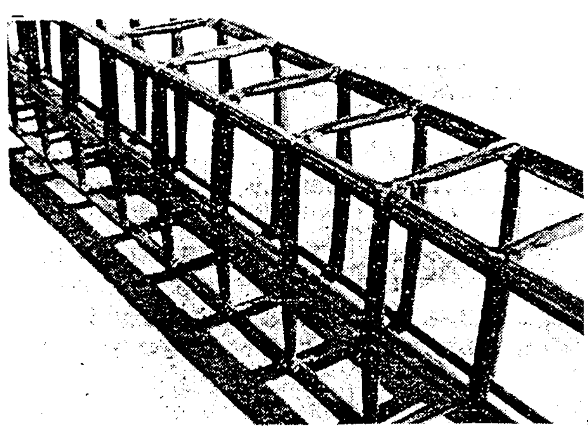


Figure 4.8. NEFMAC Grid

Table 4.6
Representative Use of NEFMAC in Existing Structures in Shotcrete

PERIOD	PROJECT	OBJECTIVE	PLACE	SPECIFICATION (DIMENSION)	SETTING AREAS (m^2)	CUMULATIVE TOTAL SETTING AREA (m^2)
5/86 - 6/86	Kumaushi Hydroelectric Power Plant	Reinforcing grids for shotcrete	Kumaushi (Hokkaido)	1.3m x 0.9m, 100mm Glass fiber Glass fiber + Carbon fiber	120	120
7/86		Reinforcing grids for shotcrete of water-conveyance tunnel at hydroelectric power plant		1.3m x 0.9m, 100mm Glass fiber Glass fiber + Carbon fiber	30	150
8/86	Kumaushi Hydroelectric Power Plant	Reinforcement for invert of water-conveyance tunnel	Kumaushi (Hokkaido)	3.82m x 0.96m, 150mm 3.82m x 0.66m, 150mm Glass fiber	60	210
10/86	Kakkonda Hydroelectric Power Plant	Reinforcing for arch, side wall and invert of water-conveyance tunnel for crack prevention	Kakkonda (Iwate Pref.)	Reinforcement for arch — Diameter 2.1m, Depth 0.9m Reinforcement for side wall — 0.9m 3.3m Reinforcement for invert — 0.7m x 3.3m Glass fiber — 100mm	220	430
11/86		Reinforcing grids for shotcrete of a tunnel-type water reservoir	(Shizuoka Pref.)	1.0m 3.0m, 150mm Glass fiber	70	500
2/87	Kumaushi Hydroelectric Power Plant	Reinforcement for arch of water-conveyance tunnel	Kumaushi (Hokkaido)	Reinforcement for arch — Diameter 4.3m, Depth 3.2m Reinforcement for side wall — 2.1m x 3.2m Grid interval — 100mm x 150mm Glass fiber	160	630
2/87 - 3/87		Reinforcing grids for shotcrete of pilot tunnel	(Iwate Pref.)	3.05m x 2.0m, 150mm Glass fiber	380	1040
4/87		Reinforcing grids for shotcrete of advancing drift	Matsudai (Nigata Pref.)	2.0m 0.75m, 150mm Glass fiber	150	1190
6/87	Kushikino Underground Petroleum Storage	Reinforcing grids for shotcrete of underground rock cavern for petroleum storage	Kushikino (Kagoshima Pref.)	2.0m x 3.0m, 150mm Glass fiber	540	1730

Table 4.7 gives a comprehensive overview of the applications of NEFMAC, and shows its versatility of use. A number of claims have been made regarding the overall cost-effectiveness of NEFMAC as compared to steel grids. An example of this is the construction of the new Shimizu building, where it was claimed that although the cost of materials was higher, significant systems-level savings were achieved due to the factors of weight (i.e., no need for specialized lifting equipment, the increased ease of placement of the structure, improved life cycle, and lower overall structural weight). However, no hard evidence has yet been seen to prove the claims as such. It must be stated that the advantages and potential for systems-level cost savings (even on a purely acquisition cost basis) make this a very attractive use of composites in the civil engineering area.

Table 4.7
Applications of NEFMAC

SERVICE PERIOD	ORDERED BY OR DELIVERED TO	R&D SUBJECT/APPLICATIONS	SPECIFICATIONS	ACTUAL APPLICATION (m^2)	AGGREGATE ACTUAL APPLICATION (m^2)
5/86 - 6/86	Electric Power Development Co., Ltd. (Kumaushi Hydroelectric Plant)	Conduit/channel tunnel for the plant: reinforcing mesh for shotcrete	G4-100P-0.9m x 1.3m H4-100P-0.9m x 1.3m	120	120
7/86	Kansai Electric Power Co., Inc. (Manami Hydroelectric Plant)	Conduit/channel tunnel for the plant: reinforcing mesh for shotcrete	G4-100P-0.9m x 1.3m H4-100P-0.9m x 1.3m	30	150
8/86	Electric Power Development Co., Ltd. (Kumaushi Hydroelectric Plant)	Conduit/channel tunnel for the plant: invert reinforcement	G19-150P-3.8m x G13-150P-1.0m G19-150P-3.8m x G13-150P-0.7m	60	210
10/86	Tohoku Electric Power Co., Inc. (Kakkonda Hydroelectric Plant)	Conduit/channel repair: arch reinforcement, side wall reinforcement, invert reinforcement (for crack prevention)	Arch: G10-100P-0.9m x 3.8m-1.05R Side Wall: G10-100P-0.9m x 3.3m Invert: G10-100P-0.7m x 3.3m	220	430
11/86 - 4/91	Asahi Glass Co., Ltd.	GRC-based OA floor reinforcing mesh	G2-60P-0.5m x 0.5m G3-30P-0.5m x 0.5m	157,090	157,520
11/87	Numazu City	Tunnel type water storage facility: reinforcing mesh for shotcrete	G4-150P-1.0m x 3.0m	70	157,590
2/87 - 3/87	Kaihatsu Koji K.K.	Survey hole for underground petroleum storage facility: reinforcing mesh for shotcrete	G3-150P-2.0m x 3.0m G4-150P-2.0m x 3.0m	380	157,970
2/87	Electric Power Development Co., Ltd. (Kumaushi Hydroelectric Plant)	Conduit/channel tunnel for the plant: arch and side wall reinforcement	Arch: G13-150P-3.2m x G16-100P-2.9m-2.2R G13-150P-3.2m x G16-100P-2.7m-2.2R Side Wall: G13-150P-3.2m x G16-100P-2.1m	160	158,130
4/87	Tokyo Electric Power Co., Ltd. (Futtsu Power Plant)	Cooling waterway corner rounding (PC structure), crack prevention reinforcement, grid reinforcement (reinforcing mesh for PC wire anchor)	Crack Prevention: G13-200P-2.2m x 2.5m G13-200P-2.2m x 0.2m Grid Reinforcement: C6-50P-0.2m x 0.2m	50	158,180
4/87 - 7/87	Daio Seishi K.K.	Coal silo: crack prevention reinforcement	G4-150P-1.7m x 3.0m	4,700	162,880

Table 4.7
Applications of NEFMAC (Continued)

SERVICE PERIOD	ORDERED BY OR DELIVERED TO	R&D SUBJECT/APPLICATIONS	SPECIFICATIONS	ACTUAL APPLICATION (m^2)	AGGREGATE ACTUAL APPLICATION (m^2)
4/87	Railroad Public Corporation	Advanced pilot tunnel (width expansion): reinforcing mesh for shotcrete	G6-150P-0.8m x 2.0m	150	163,030
8/87	Okabe Doboku K.K.	Cut soil surface cap	G4-150P-2.0m x 3.0m	80	163,110
8/87 -	Iwata Shokai K.K.	Support mesh for digester filler	G2-34P-1.1m x 1.2m G3-34P-1.1m x 1.2m	4,570	167,680
12/87 -	Tokyo Gas Co., Ltd.	Underground LPG storage facility excavating and reinforcing, reinforcing mesh for shotcrete	G4-150P-2.0m x 3.0m, 1.75m x 2.0m	14,340	182,020
3/88	JR East Japan Railway Company	Reinforcing mesh for GRC-based trough, and others	G2-60P G2-50P x 150P G3-50P x 200P	148,020	330,040
4/88 -	Tokyo Electric Power Company (Saiko Power Plant)	Reinforcement of surface: reinforcing mesh for shotcrete	G2-50P-2.0m x 3.0m	270	330,310
4/88 - 4/91	Joint Venture of Shimizu Corp., Hazama-Gumi Ltd., Obayashi Corp., Maeda Corp., Railroad Public Corporation and Fujita Corp.	Underground petroleum storage facility (operation, water seal, main tunnel): reinforcing mesh for shotcrete	G3-150P-2.0m x 3.0m G4-150P-2.0m x 3.0m	491,000	821,310
5/88 - 8/88	Joint Venture of Zenitaka Corp., Uemura, and Marufuku (Kushikino)	Underground petroleum storage facility (tunnel for emergency exit)	G3-150P-2.0m x 3.0m	6,200	827,510
6/88 - 7/91	Joint Venture of Kajima Corp., Nishimatsu Construction Co., Kumagai Gimi Co., Okumura Corp., Aoki Corp., and JDC Corporation (Hisaji)	Underground petroleum storage facility (operation, water seal, tunnel for emergency exit): reinforcing mesh for shotcrete	G3-150P-2.0m x 3.0m G4-150P-2.0m x 3.0m	108,000	935,510
11/88	Nihon Silo K.K.	Reinforcement for pier protection sheet	G19-175P-4.2m x G19-200P-2.3m	40	935,550
12/88 - 6/91	Joint Venture of Taisei Corp., Toda Construction Co., Tobishima Corp., Sato Kogyo Co., and Konoike (Kikuma)	Underground petroleum storage facility (operation, water seal, main and emergency tunnels)	G3-150P-2.0m x 3.0m G4-150P-2.0m x 3.0m	146,000	1,081,550

Table 4.7
Applications of NEFMAC (Continued)

SERVICE PERIOD	ORDERED BY OR DELIVERED TO	R&D SUBJECT/APPLICATIONS	SPECIFICATIONS	ACTUAL APPLICATION (m^2)	AGGREGATE ACTUAL APPLICATION (m^2)
12/88	Tokyo Electric Power Company (Utunomiya Central Line Works)	Tunnel for power transmission: reinforcing mesh for shotcrete	G3-150P-2.0m x 3.0m	1,300	1,082,850
2/89	University of Tokyo, Earthquake Research Institute	Geomagnetic Observatory: foundation reinforcement (non-magnetic)	Foundation Beam: G10-100P-2.0m x 3.0m Slab: G10-200P-2.0m x 3.0m Corner: G10-100P-0.4m x 0.7m	260	1,083,110
2/89	JR West Japan Railway Company	Tunnel wall repair: reinforcing mesh for shotcrete	G5-150P-2.0m x 3.0m	360	1,083,470
2/89	Alpha Corporation Technology	Reinforcing mesh for permeable sheets	G3-29P-0.3m x 0.3m G4-29P-0.3m x 0.3m	850	1,084,320
2/89	Toyo Kosoku Tetsudo K.K.	Temporary tunnel (width expansion): reinforcing mesh for shotcrete	G2-50P-1.1m x 2.0m	2,700	1,087,020
5/89	Shimizu Chisho K.K.	Reinforcement for curtain walls	H8-100P-2.0m x 3.2m	130	1,087,150
7/89	JR East Japan Railway Company	Tunnel wall reinforcement: reinforcing mesh for shotcrete	G2-150P-1.5m x 2.0m	150	1,087,300
10/89	Meteorological Agency	Geomagnetic Observatory: foundation reinforcement (non-magnetic)	G10-200P-1.6m x 3.2m	20	1,087,320
11/89	Jumonji Doboku K.K.	Temporary tunnel (width expansion): reinforcing mesh for shotcrete	G2-50P-1.1m x 2.0m	220	1,087,540
12/89	Shimizu Corp.	Cut soil protection: reinforcing mesh for shotcrete	G5-40P x 150P-2.0m x 3.3m	5,710	1,093,250
12/89 - 6/90	Joint Venture of Sumitomo Corp. and Shikoku Tsushin (Kikuma)	Underground petroleum storage facility (service tunnel): reinforcing mesh for shotcrete	G3-150P-2.0m x 3.0m G4-150P-2.0m x 3.0m	7,200	1,100,450
1/90	Kamioka Kogyo K.K.	Reinforcing mesh for shotcrete	G2-100P-1.5m x 3.0m	90	1,100,540

Table 4.7
Applications of NEFMAC (Continued)

SERVICE PERIOD	ORDERED BY OR DELIVERED TO	R&D SUBJECT/APPLICATIONS	SPECIFICATIONS	ACTUAL APPLICATION (m^2)	AGGREGATE ACTUAL APPLICATION (m^2)
2/90 - 8/90	Joint Venture of Kajima Corp., Taisei Corp., and Shimizu Corp.	Underground LPG storage and test facility: reinforcing mesh for shotcrete	G4-150P-2.0m x 3.0m	1,680	1,102,220
3/90	Toyohane Kozan K.K.	Reinforcing mesh for shotcrete	G2-50P-2.0m x 30.0m	3,100	1,105,320
3/90	JR East Japan Railway Company	Tunnel wall repair: reinforcing mesh for concrete	G10 x G6-150 x 80-1.58m	890	1,106,210
5/90	Joint Venture of Kajima Corp. and Kobayashi Metals, Ltd.	Reinforcing mesh for shotcrete	G4-150P-1.5m x 2.0m	150	1,106,360
5/90	Teihyu K.K.	Reinforcement for floating pier concrete	G2-50P-2.0m x 10.0m	1,380	1,107,740
5/90	Tokyo Electric Power Co., (Kashiwazaki Nuclear Power Plant)	Reinforcing mesh for temporary concrete sheet	G3-50P-2.0m x 3.0m	1,400	1,109,140
9/90	Hokkaido Power Co.	Conduit tunnel repair	G4-150P-1.1m x 2.0m 1.5m x 2.0m	120	1,109,260
10/90	Electric Power Development Co., Ltd. (Akiba III Power Plant)	Reinforcing mesh for shotcrete	G4-150P-2.0m x 3.0m	300	1,109,560
12/90	Hokkaido Electric Power Co.	Conduit tunnel repair	G4-150P-2.0m x 3.0m 0.89m x 3.0m	2,390	1,111,950
3/91	National Institute of Polar Research	Showa Base: structural reinforcement for control tower wall, floor, and pillar	G10-100P 1.4m x 3.0m G6~G14-100P 2.0m x 3.0m G16 x G10 450 x 2.0m	970	1,112,920
4/91	JR East Japan Railway Company	Reinforcement of railroad crossing pavement (non-magnetic)	G10-100P-1.5m x 1.9m 1.0m x 1.9m	80	1,113,000
5/91	Shimizu Corp.	Shielding work: reinforcement for arrival shaft walls	G13-150P-1.3m x 4.6m G16-150P~300P-2.2m x 4.6m H19-150P-1.3 x 4.45m	50	1,113,050

Table 4.7
Applications of NEFMAC (Continued)

SERVICE PERIOD	ORDERED BY OR DELIVERED TO	R&D SUBJECT/APPLICATIONS	SPECIFICATIONS	ACTUAL APPLICATION (m^2)	AGGREGATE ACTUAL APPLICATION (m^2)
5/91	Fukuda Gumi K.K.	Reinforcement for hot spring tunnel	G13-200P-2.8m x 5.4m-6.1R 2.8m x 4.9m-6.1R G2-50P-2.0m x 10.0m	700	1,113,750
5/91	B by B K.K.	Mesh for pond water purifier	G6-100P G10-100P G13-75P G2-50P	1,000	1,114,750
6/91 - 3/92	Joint Venture of Shimizu Corp., Sumitomo Corp., and Tamehiro Kensetsu	Reinforcing mesh for dam surface shotcrete	G4-100P-2.0m x 3.0m	23,160	1,137,910
8/91	New Hampshire University, Federal Highway Administration	Reinforcement for bridge surface	C19~C22-1.2m x 3.6m H19~H22-1.2m x 3.6m	1,230	1,139,140
8/91	Hokkaido Electric Power Co.	Reinforcement for conduit tunnel repair	G11-150P-0.81m x 3.1m 1.75m 4.2m	890	1,140,030
10/91	Coastal Development Institute of Technology	Harbor structure testing	C12 x C18 W H L 0.4m x 0.41m x 3.23m C10 x C16 x C10 W H L 0.4m x 0.41m x 1.63m 0.4m x 0.41m x 1.63m	20	1,140,050
1/92	Nippon Denso Co., Ltd.	Close-open operation of shutters, non-magnetic floor reinforcement	G19-100P-1.2m~1.7m x 4.0m~6.8m	230	1,140,280
1/92 - 2/92	Mitsubishi Heavy Industries, Ltd.	Reinforcing mesh for floor	G4-150P-2.0m x 3.0m	6,800	1,147,080
2/92	Joint Venture of Aoki Corp., Shimizu Corp., Nishimatsu Construction Co., Kaihatsu Koji and Kuniba Gumi (Okinawa)	Sea-water pumped-storage power generation facility (validation test): reinforcing mesh for shotcrete	G4-150P-1.75m x 2.0m	100	1,147,180

CHAPTER 5

MATERIALS

Jon B. DeVault

INTRODUCTION

In 1991, a JTEC Panel on Advanced Composites surveyed the status and future directions of Japanese high-performance ceramic and carbon fibers and their composites in metallic, intermetallic, ceramic, and carbon materials (Diefendorf 1991). An earlier JTEC study in 1986 also assessed the advanced material technology in Japan (Economy 1986). The focus of this study is an assessment of Japan's structures manufacturing technology, so only a few material companies were visited; nevertheless, the panel made an adequate assessment of the status and future direction of Japan's advanced polymer matrix composites (PMC) materials technology.

As was pointed out in the 1991 JTEC report, Japan has an ambitious space program, which includes a space shuttle and participation in a supersonic civilian aircraft. This space program is still a major factor in their material development efforts.

The Japanese have seen little to no impact on their carbon fiber market volume due to the slowdown in the U.S. defense market. Although it does not appear that they have included any major penetration of the civil engineering market through 1995 in their carbon fiber market forecasts, they are clearly the world leader in pursuing these applications.

CARBON FIBER

Table 5.1 compares a February 1992 Toray worldwide market forecast for pan-based carbon fiber with a similar U.S. SACMA study made at the same time. There are some minor differences in the forecasted uses in 1989 and 1990, but the forecasts are essentially identical from 1991 to 1995. Table 5.2 is Toray's assessment of the world production capacity for pan-based carbon fiber. It too is in agreement with U.S. assessments. These two tables indicate that the world market utilized just over 50% of capacity in 1992 and would utilize only 81% in 1995, assuming no new capacity was added.

It is also interesting to look at the Japanese market versus the Japanese capacity in 1992 (27% utilization) and in 1995 (33% utilization) to see how important exports are to their carbon fiber industry. The U.S. market is projected to grow by 74% between 1992 and 1995, whereas the Japanese market is forecasted to grow only 21%.

Toray, which entered the carbon fiber market in 1969, is now the recognized world leader in carbon fiber. Toray is totally integrated -- from precursors to spinning, carbonizing to graphitizing, weaving and braiding preprocess -- and is aggressively expanding its fabricated structures business.

Table 5.1
Worldwide Demand for Pan-Based Carbon Fiber
(Tons/Year)

	1989	1990	1991	1992	1993	1994	1995
North America	2500 (2363)	2400 (2227)	2200 (2136)	2300 (2273)	2800 (2773)	3400 (3364)	4000 (3909)
Europe	1100 (909)	1250 (1045)	1260 (1181)	1400 (1409)	1550 (1590)	1750 (1864)	2000 (2045)
Far East & Others	1090 (1090)	1200 (1181)	1350 (1318)	1400 (1409)	1450 (1455)	1550 (1590)	1650 (1727)
Japan	1110 (1090)	1250 (1181)	1360 (1275)	1400 (1364)	1500 (1455)	1600 (1590)	1700 (1682)
TOTAL	5800 (5454)	6100 (5636)	6170 (5909)	6500 (6454)	7300 (7272)	8300 (8409)	9350 (9363)

Source: Top numbers from February 1992 Toray Ind., Inc. forecast; numbers in parens from February 1992 SACMA forecast.

Table 5.2
World Production Capacity for Pan-Based Carbon Fiber
(Tons/Year)

ASIA	Toray	2,250
	Toho	2,020
	Asahi Kasei	450
	Mitsubishi Rayon	500
	Taiwan Plastic	230
Subtotal		5,450
U.S.A.	Hercules	1,715
	BASF	1,350
	Amoco	850
	Akzo	360
	Grafil	320
	Zoltek	60
Subtotal		4,655
EUROPE	Akzo	500
	Soficar	700
	Sigri	100
	R.K. Carbon	100
Subtotal		1,400
TOTAL 11,505 tons/year		

In 1984, Toray opened a carbon fiber operation in France and will shortly commission a prepreg plant in the U.S. The company has the widest available range of carbon fibers, with eight different strength and modulus combinations. Toray's family of carbon fibers is shown in Figure 5.1. Their fibers have extremely low rates of deviation in product quality, which ensures superior handling and processability; this is a result of Toray's comprehensive product quality control system.

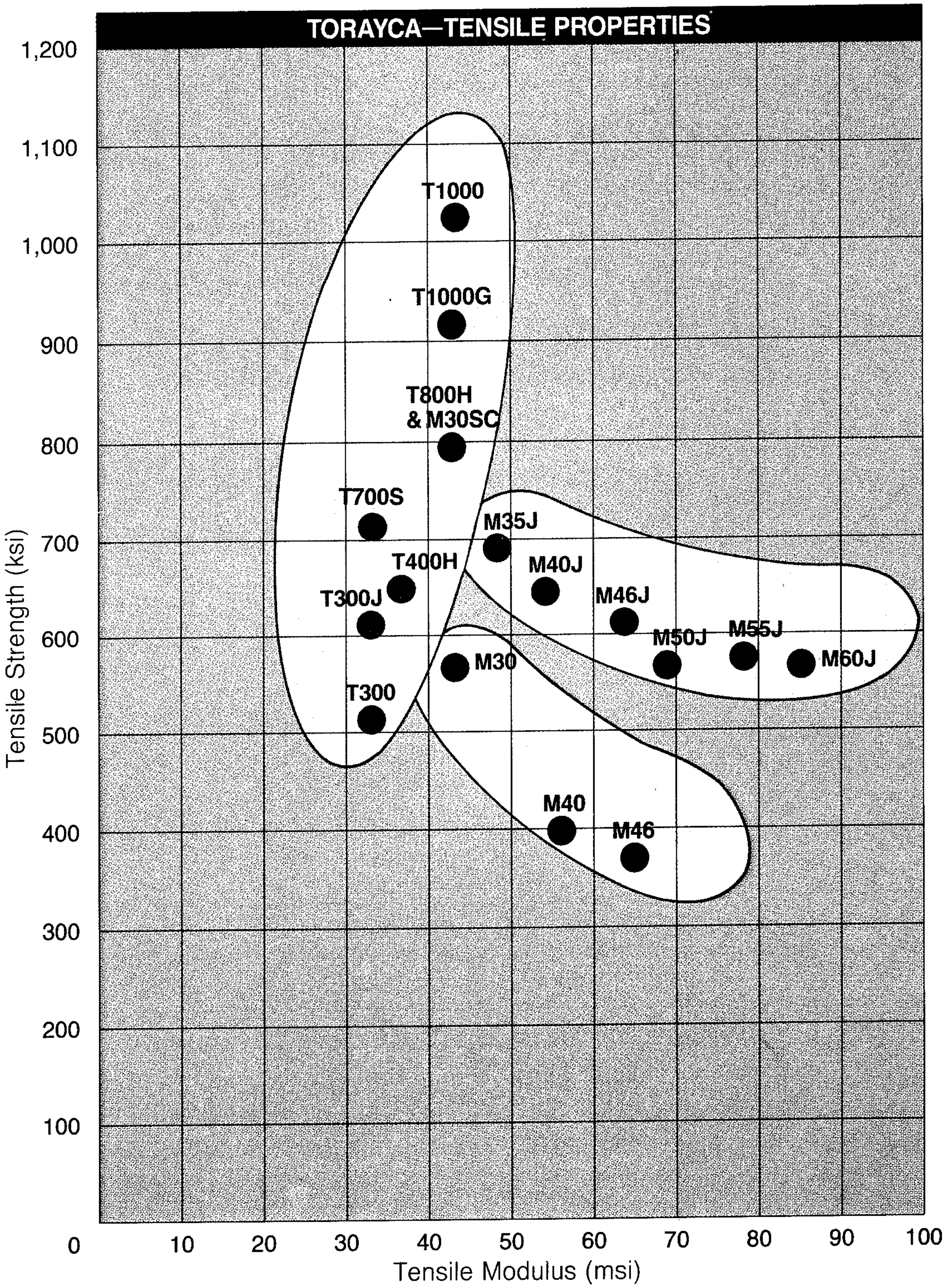


Figure 5.1. Toray's Family of Carbon Fibers

Table 5.3 summarizes the world production capacity for pitch-based carbon fiber, which is almost totally based in Japan. The source of the pitch precursor is coal for three suppliers, and petrol for the other five. The economics of pitch versus pan-based fiber is not clear.

Table 5.3
World Production Capacity for Pitch-Based Carbon Fiber
(Tons/Year)

ASIA	Kureha Chemical	900
	DONAC	300
	Mitsubishi Kasei	500
	Nippon Oil	50
	Nippon Steel	50
	Tonen	12
	Petoca	12
U.S.A.	Amoco	230
TOTAL	**2,054 tons/year**	

Source: Toray, August 1992

The fiber property data for Mitsubishi Kasei's coal tar pitch-based carbon fiber, Dialead, is shown in Table 5.4. The fiber is available in chopped and continuous form with tensile moduli ranging from 25 to 110 million psi. Composites made with these fibers would exhibit marginal interlaminar and tensile strengths and very low compressive strengths when compared to pan-based fibers.

MATRIX RESINS

Although Toray has done an excellent job in developing a tough epoxy resin system for carbon fiber, it was apparent that the matrix R&D focus in Japan is high-temperature resins. This was evident at all of the aerospace primes visited and at Mitsui Toatsu Chemical, Inc. This is to support Japan's ambitious space program mentioned earlier.

The focus on high-temperature resins was also obvious by the temperature and pressure capability of all the autoclaves that have been recently installed in Japan. While Mitsui Toatsu presented matrix research activities including glass fiber in polypropylene, their major effort was on a thermoplastic polyimide matrix for carbon fiber for PX/T800. Table 5.5 compares the properties of the PX/T800 composite with

those of PEEK/AS4 and an epoxy with T300. These materials offer outstanding heat resistance, excellent toughness, and good processability.

Table 5.4
Mitsubishi Kasei Dialead
Coal Tar Pitch-Based Carbon Fiber

TYPE	TENSILE STRENGTH (KSI)	TENSILE MODULUS (MSI)
CONTINUOUS FIBER		
K321	290	26
K133U	485	64
K135U	520	90
K137U	540	93
K139U	570	110
K13BU	570	120
CHOPPED		
Type 223	340	30
Type 661	260	25

Table 5.5
PIX (Thermoplastic Polyimide) CF Prepreg
(Mitsui Toatsu Chemicals, Inc.)

MECHANICAL PROPERTIES				
Matrix Resin	Compression Strength (kgf/mm^2)	Tensile Strength (kgf/mm^2)	CAI Strength (kgf/mm^2)	Continuous Use Temp. (°F)
PIX/T-800[1]	143	251	36,2	450
PEEK/AS-4[2]	111	213	31	300
Epoxy/T-300[3]	140	143	14	<300

1. Outstanding Heat Resistance
2. Excellent Toughness
3. Good Processability

Mitsui Toatsu has broad-based cooperation with companies and universities in Japan, Europe, and the U.S. It was very interesting that Mitsui Toatsu has annual sales of approximately $3.3 billion, spends $190 million on R&D (5.7% of sales), and has only 5,475 employees, 25% of whom are in R&D.

RESIN TRANSFER MOLDING (RTM)

Resin transfer molding was being pursued by most of the aerospace primes and by several universities, including the Textile Science Group at the Kyoto Institute of Technology, but of particular interest was the Three-D Composites Research Corporation. This research group was established in March 1988 with the following investing companies:

- Mitsubishi Electric
- Nippon Steel
- Toyoda Automatic Looms Work, Ltd.
- Mitsubishi Rayon
- Arisawa Manufacturing Co.

The charter of the group is to develop 3-D preforms and molding technologies with funding of $16 million over a six year period. A short paper that summarized their efforts and outlined the results of their research to date was obtained.

A rod-type 3-D loom has been developed to make a block that smaller parts can be cut from, and another for making cloth. The group is also working on matrix systems for RTM that include a concept where the preform includes "thin impregnated rods," which created "zoned hardening" and irregular-shaped products with the process.

SUMMARY OF FINDINGS

- The U.S. and the Japanese agree on market size for pan-based carbon fibers.
- The Japanese are still aggressively pursuing pitch fiber.
- The Japanese appear to be doing significant work on RTM.
- The Japanese matrix R&D focus is on high-temperature resins.
- The Japanese aerospace material focus is still on performance versus cost.
- The Japanese are the clear world leaders in pursuing civil engineering applications for carbon fiber.

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CHAPTER 6

MANUFACTURING / PROCESSING SCIENCE

V. M. Karbhari

SCOPE OF THE STUDY

It should be made clear at the outset of this chapter that the basis for the term *manufacturing science* lies more in the scientific and technological culture of the U.S. than in that of Japan. In the U.S., as will be explained later, manufacturing science is taken to be distinct from product development. However, the boundaries between the two are not as distinct in Japan. In fact, it may be stated that both are subsets of an overall science (if that term may be used at all), the overall product management process, which includes all aspects of what we may term basic research, development, and productization. In that vein, readers are cautioned that the subject matter of this chapter should be read in congruence with that of the next -- the differentiation between manufacturing science and product development is being made here more from the author's U.S. symbolism than from a Japanese perspective. Together, however, the two chapters provide an insight into the development of composites manufacturing from an integrated process and product viewpoint.

This document will (1) define key terms as they are used in the U.S. and Japan, placing special emphasis on the difference in perspective, (2) give examples of the basic and applied research seen by the team in the area of polymer-matrix composites manufacturing and related areas, and (3) discuss the development of manufacturing technology. Technology policy and the structure of basic research in Japan, as well as a glimpse of what the future may hold in these areas, are discussed in the next chapter. The reader should note that this document should

be viewed not as a policy document but as a source of information. It is by no means comprehensive but does serve as an initial documentation of the differences in approach and status in composites manufacturing between the two countries.

INTRODUCTION

With respect to this document, *manufacturing science* is defined as the understanding of the process by which material, labor, energy, and equipment are brought together to produce a product having a greater value than the sum of the individual inputs. The emphasis here is on the approach needed to understand and control inputs required for a specific output. In itself, it recognizes the coupling of the three decision areas of materials, configuration, and processes, in that a choice of a specific aspect or attribute within any of these classes necessitates simultaneous choices in the others, due to their close interdependence. The concurrency of decisions necessitates the development of an integrated science base for the manufacturing of composites so as to enable optimization and development of a system before actual manufacture. This is in sharp contrast to the build-test-fix methodology attributed to metals manufacturing. In short, it requires an understanding of the links between various aspects, as shown in Figure 6.1, as well as their integrated effect on manufacturing in terms of metrics, such as life-cycle concerns, fundamental laws of physics and chemistry, reliability, quality, and cost.

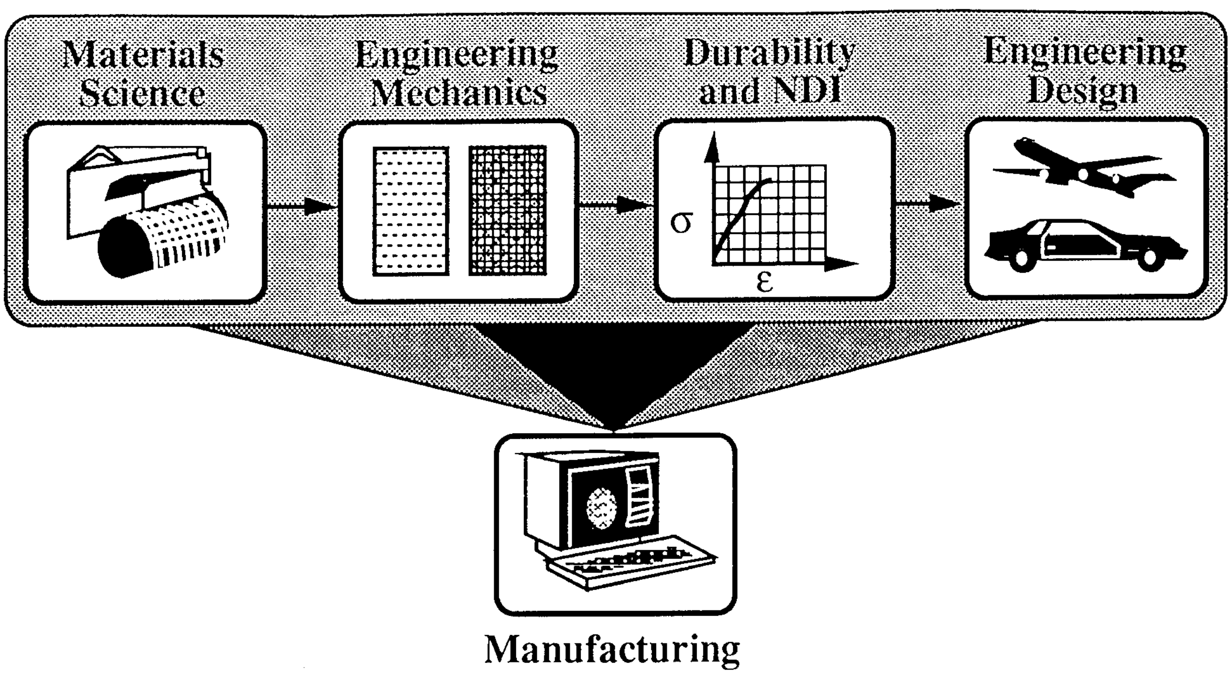


Figure 6.1. Interaction of Manufacturing With Other Key Areas (Univ. of Delaware)

At the outset, it is interesting to compare the two models that could hypothetically be proposed for "intelligent manufacturing of polymer-matrix composites" using a manufacturing science base. On the one hand, we have an approach common in the U.S. (Fig. 6.2 -- as developed at the University of Delaware, based on work being conducted at the Center for Composite Materials). On the other hand, we could consider one adapted from the Japanese industry at the University of Tokyo (Fig. 6.3). The first emphasizes the use of process models and simulation as a short cut and an efficient mechanism to process understanding driven by the latest advances in computers, AI, modeling, and sensor technology. The second emphasizes the integration of design, materials, fabrication, and inspection through knowledge gained by experimentation and routine, detailed inspection.

Figure 6.2 shows the conceptual ideal manufacturing system (the U.S. model), wherein process understanding drives the idea of integrated manufacturing brought about by appropriate use of process models, sensors, control systems, and statistical and quality control measures.

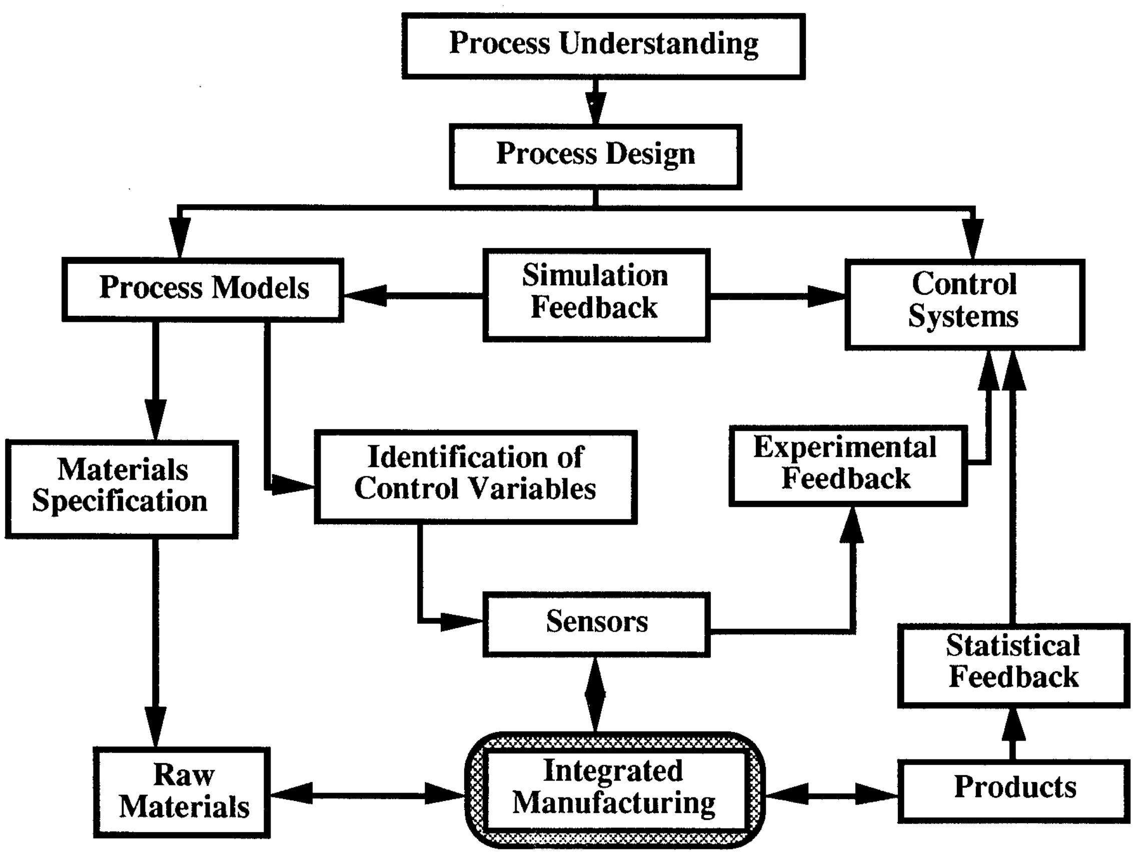


Figure 6.2. Schematic of an Ideal Manufacturing System

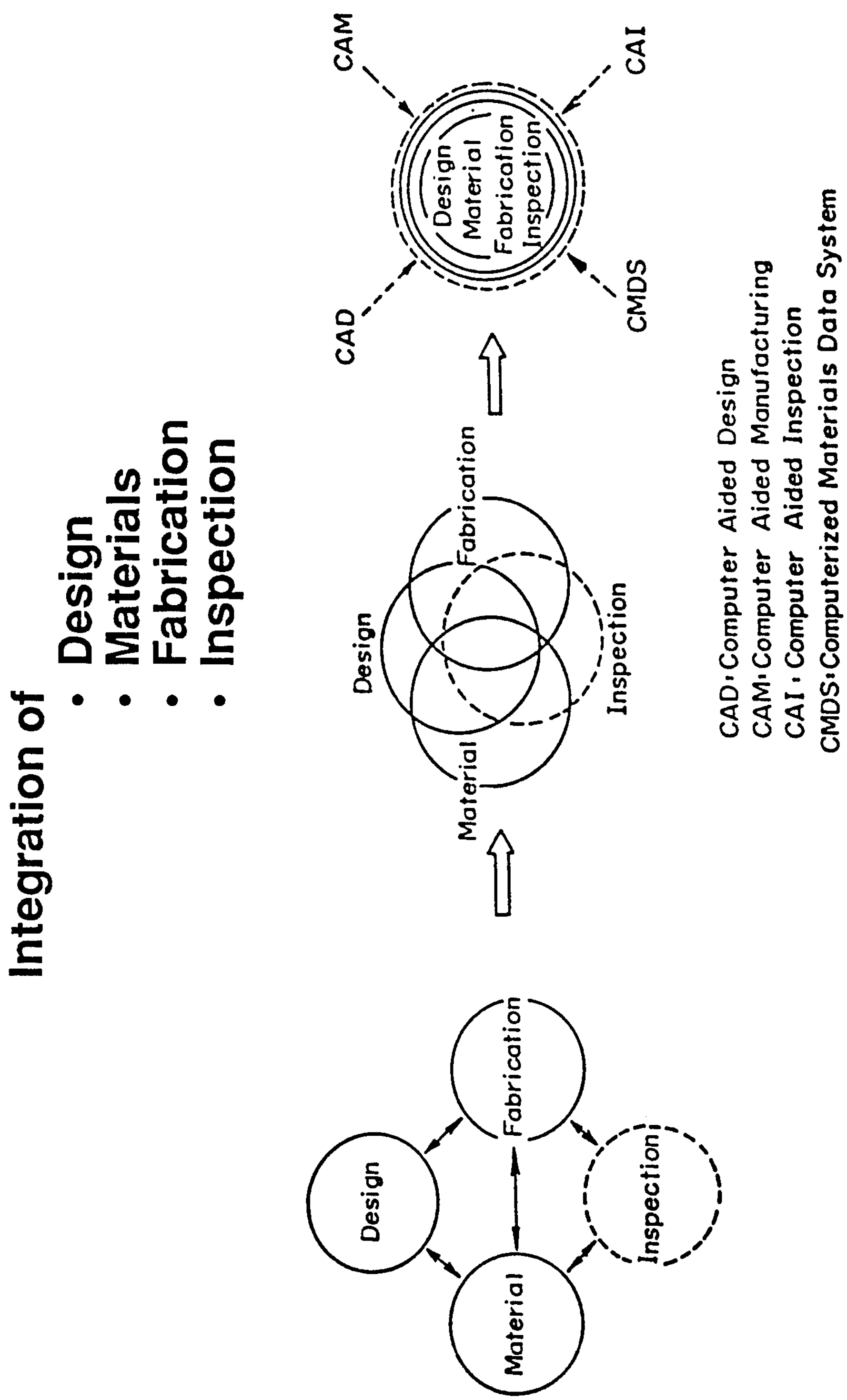


Figure 6.3. An Idealized Manufacturing Science System (University of Tokyo version)

Fully developed process models, coupled with empirical results and analysis (Fig. 6.4), lead to the quick development of a system wherein simulation serves as an efficient aid to focusing the design space for directed experimentation (Fig. 6.5).

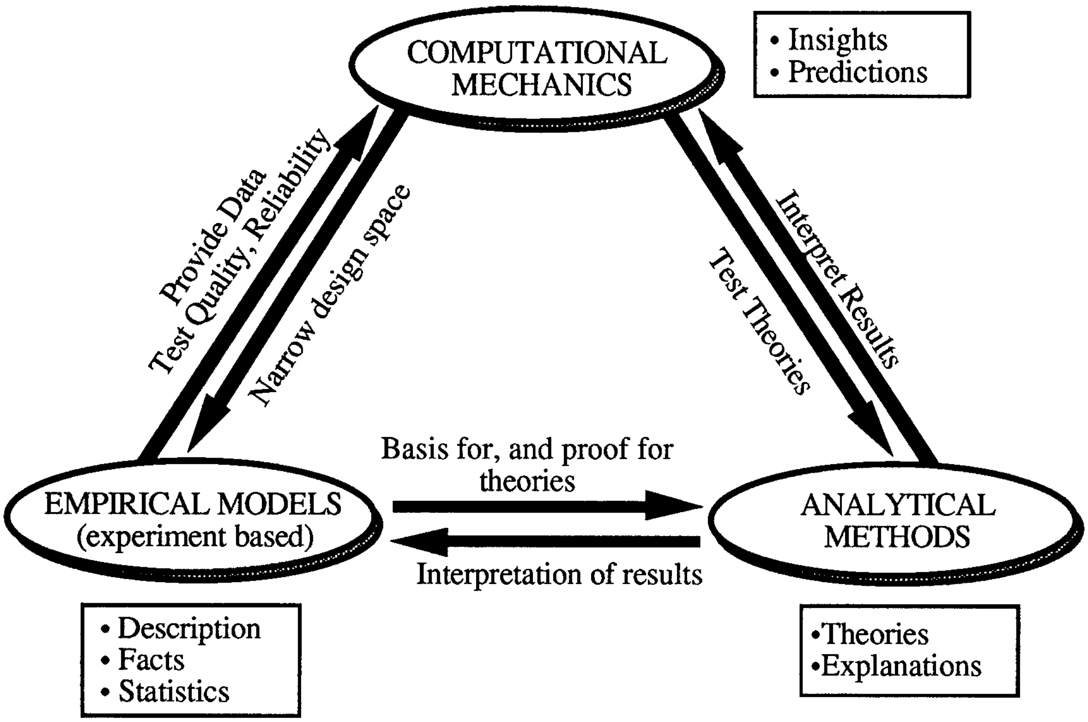


Figure 6.4. Use of Various Aspects to Aid in the Development of a Science Base

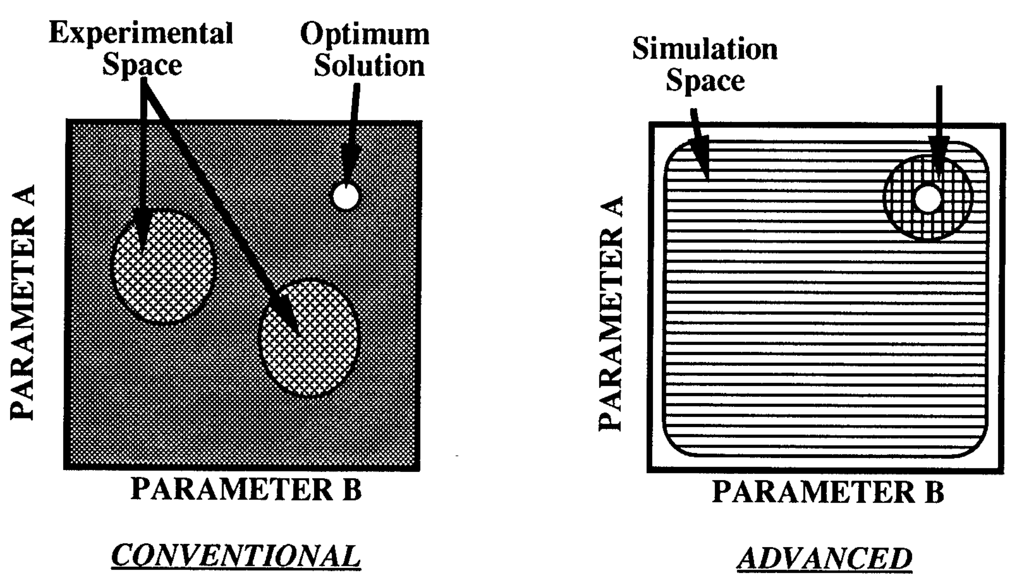


Figure 6.5. Simulation of Processes Can Aid in Directing Experimentation

It also ensures that experiments conducted for process and materials development and validation are as close as possible to the overall optimum solution rather than in isolated pockets of the design spaces. The U.S. model is based on the premise that the development of advanced models is key to the development of manufacturing systems and must be done hand-in-hand with advances in sensor and control technology. It may even be described as a system that reaches for perfect understanding before product experiments are allowed to occur -- a factor that may be hindering significantly the U.S. capability to "go to product early," since expensive experimentation is often not deemed suitable (the underlying reasons will be explained in the next chapter), even if there is a high-payoff advantage to taking a high-risk gamble.

The Japanese analog (Fig. 6.3) does make extensive use of computers, in terms of both computer-aided design (CAD) and computer-aided inspection (CAI), but places direct and primary emphasis on the development of an experimental database that would allow one to go directly to the first-generation product without using detailed process models or control strategies.

As a specific example, scientists at Nippon Steel preferred to directly wind a large number of thick cylindrical parts to gain an understanding of the process and end product quality rather than use existing codes because of time and economical constraints! It was felt that the time taken to adequately train an engineer in the use of the codes could be better spent on actual experimentation on large-scale specimens, and that the results of direct manufacturing would be more believable to the end user (or customer) than the results of a paper simulation. This is not a rule and should not be taken to mean that this specific company (or any other Japanese company) does not use simulations -- only that direct experimentation on large specimens is often deemed more desirable at the early stages of product development. It should be emphasized here that whereas in the U.S. manufacturing science is taken to be an academic or advanced industrial research task, in Japan it is seamlessly integrated into product development.

For the overall development of an integrated manufacturing/processing schema as shown in Figure 6.4, it is essential that the features of models, sensors, and control be integrated into the previously described coupled decision factors of materials, configuration, and processing (Fig. 6.6). The model provides an understanding of the physics and chemistry involved and explains the relationship between dependent and independent variables. The sensors provide information related to the state of the materials and process variables so as to facilitate process information feedback. The control function maintains quality through the use of data provided by sensors as input to the models and manages the product realization process to achieve the design profile. The development of a manufacturing science base necessitates the development of all the features discussed above.

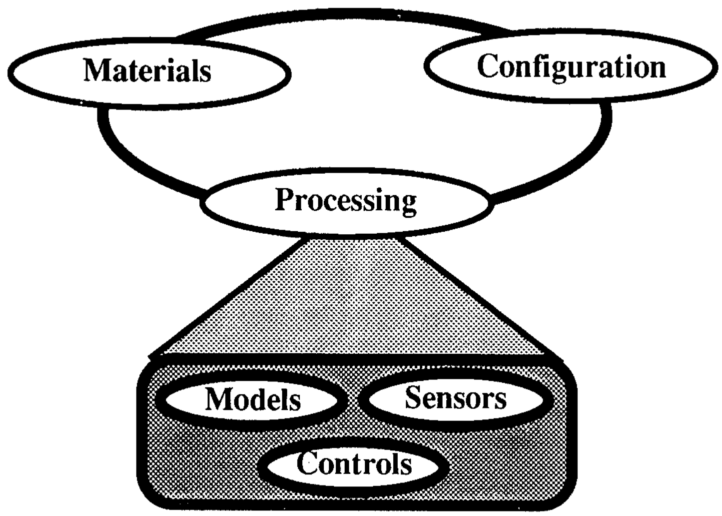


Figure 6.6. The Coupling of Design Factors With Processing Science

In contrast, the Japanese analog (Fig. 6.7) emphasizes attention to people factors and experience through rules gained by extensive experimentation and detailed study of materials and processes. The study is done with attention to the most minute detail, and the entire system is often designed keeping in mind the need for human interaction. The attention to detail, as alluded to in the earlier chapters, is a focus within such a model.

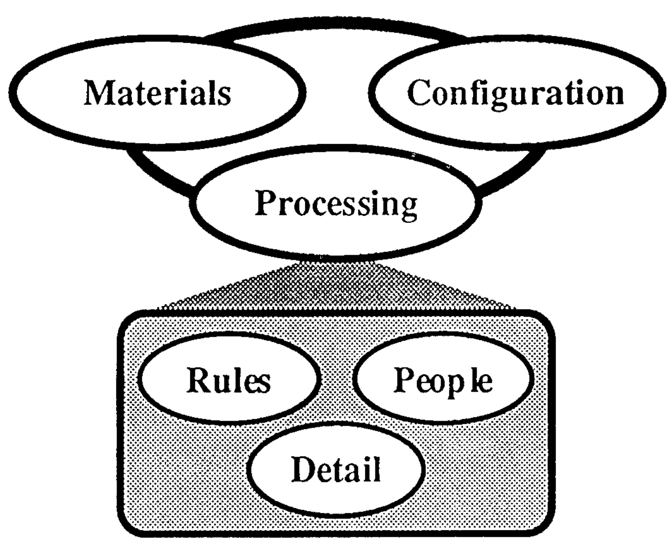


Figure 6.7. The Coupling of Design Interactions for Intelligent Manufacturing

In applying a concurrent engineering methodology to a process like resin transfer molding, the U.S. approach to the problem is through simulations for tool design, preform design, infusion, and cure. The part is ideally analyzed on a computer before actual processing. In Japan, on the other hand, there is an intrinsic application of concurrent engineering to RTM, simply by virtue of the way the Japanese approach the problem through the use of innovative machines, structures for which they have extensive data, and rules for tool design based on experience and attention to detail. The Japanese experience with experimentation leads them to apply this knowledge in a concurrent engineering environment without complete dependence on simulations. The end goal is always zero defect manufacturing, rather than mere metrics such as quality control, reliability, economics, and maintainable production schemes, which are already intrinsically built in. In short, the Japanese approach can be characterized as the use of a building-block approach wherein extensive experimentation and detailed trade-off analyses are conducted at each level to achieve an in-depth understanding of materials, processing, and design through attention to people factors and detail at all stages of the development of a manufacturing science base.

Before providing specific examples of the developments in Japan under the topic of this chapter, it is interesting to provide a focus by emphasizing that developments in composites will be successful only if an understanding of available technology is facilitated to ensure rapid commercialization and use of the materials and processes in a reliable and cost-efficient manner (which at first glance would seem to be the route being followed by the Japanese). Table 6.1 pinpoints expected developments in a number of important composite processes as driven through the advancement of materials and process understanding.

Table 6.1
Expected Developments in Composite Processes

TECHNICAL ATTRIBUTE	Filament Winding	Pultrusion	RTM	SRIM	SMC	Thermoplastic Sheet Molding or Stamping
Improved Materials	+	+	++	++	++	o
Process Control	+	+	+++	++	++	+++
Automation	++	o	+++ (Preforming)	o	++	+++
Mold Design	+	o	+++	++	+	+++

Key: "o" = little or no activity; "+" = some activity; "++" = considerable activity; "+++" = intense developments.

Table 6.2 depicts the level of the U.S. capability in the broad area of composites manufacturing determined by the DoD Key Technology Plan of July 1992. It will prove useful to keep this in mind throughout the study, as it actually represents a fairly accurate snapshot of the state of the U.S. composites industry vis-a-vis its global counterparts.

Table 6.2
Comparison of Capabilities

AREA	Europe	Japan	USSR and Pre-1991 Communist Bloc	Others
Structural Materials, Processing and Inspection	+++o	+++o	+++	++ China, India, Israel, S. Korea, Switzerland, Sweden
High Temperature and Anti-Armor Materials	+++o	++o	+++	++ Austria, Israel, Sweden
Electromagnetic and Armor Protection Materials	+++o	++o	++++	++ China, Israel
Electronic, Magnetic and Optical Materials	+++o	++++o	++	++ Australia, China, India, S. Korea, Sweden, Switzerland
Special Function and Bimolecular Materials and Processes	+++o	+++o	+	++ Austria, China, Switzerland

Key:

++++	Broad technical achievement; capable of major contributions
+++	Moderate technical achievement; possible leadership in niche area; capable of important contributions
++	Generally lagging
+	Lagging in all important aspects; unlikely to contribute prior to 2002
o	Foreign capability increasing at a similar rate to the U.S.

Source: DoD Key Technology Plan, July 1992

PROCESS MODELING AND SIMULATION

Manufacturing processes are based on sets of activities that transform a given set of raw materials into a final state through a chain of activities known as the *materials transformation process* (Fig. 6.8).

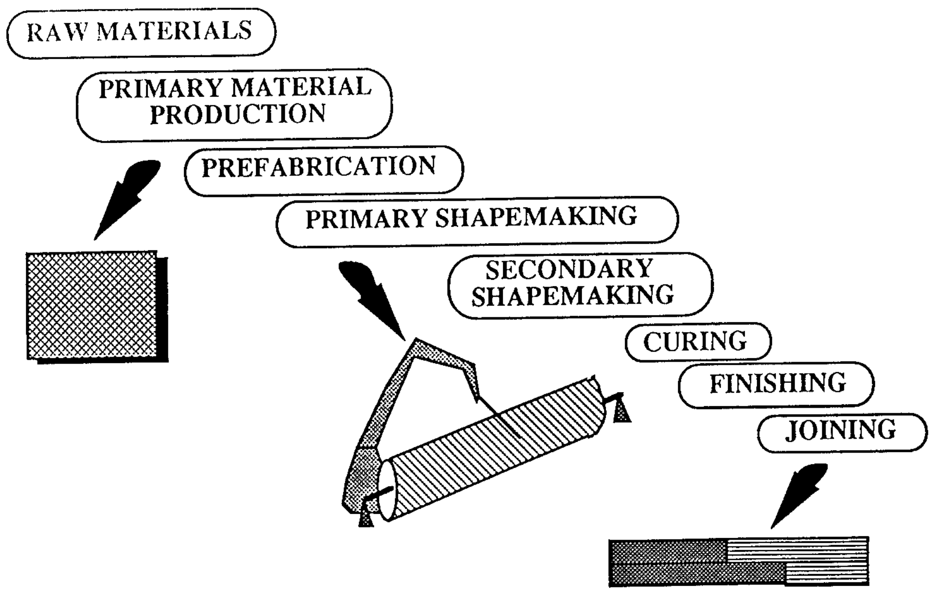


Figure 6.8. The Materials Transformation Process

The most critical frontier in advanced materials today is the gap between the ability to make and the fundamental understanding of the process needed for its rapid and reliable commercialization. Following Hahn (1991), an overview of process modeling is depicted in Figure 6.9.

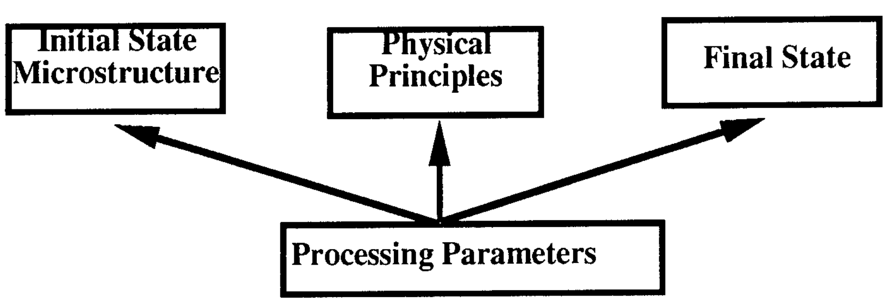


Figure 6.9. The Principles of Process Modeling

The prime consideration in all composites processes is the evaluation of cure kinetics and degree of cure through equations such as:

$$\frac{d\phi}{dt} = \left(k_1 + k_2 \phi^m\right)\left(1-\phi\right)^n$$

Viscosity and gel as well as other properties are a function of degree of cure and temperature:

$$\left(\rho, \alpha, c, K, \mu, S\right) = f\left(\phi, T\right)$$

Generically, process modeling involves the solution of equations of balance of mass, energy, and linear momentum in addition to those listed above. Table 6.3 lists a number of models and investigators for specific process model sections related to autoclave cure, filament winding, pultrusion, and RTM.

In the recent past, processing models have been developed in a variety of areas and could very well be the subject of an in-depth review, not within the scope of this section. However, to do some justice to the topic, a brief review of modeling activity in the area of autoclave compression molding, RTM and compression molding is given herein (Table 6.4), suggesting the state of modeling in each area.

The interested reader is referred to the excellent reviews of Loos and Springer (1986) and Tucker (1987), Bruschke (1992), and Advani (1989), respectively for the three processes outlined in the table above. In addition, the activity of filament winding is fairly well characterized from the simulation of fiber path to the resolution of cure and compaction on residual stresses. There is increasing activity in the area of pultrusion to develop models for powder impregnation, and an increasing use of micromechanics models at the unit-cell level to predict permeability and to study micro-flow of resins through fabric bundles in RTM. It is of interest to note that although there is work being conducted in these areas in Japan, most of the simulations being used are based on the ones mentioned above. As an example, it could be mentioned that Mitsubishi Kasei routinely used the LIMS software (developed at the Center for Composite Materials, University of Delaware) to simulate flow and resin infusion during the development of an electric scooter body,

Table 6.3
State-of-the-Art Modeling
in Some Important Composite Processes

PROCESS ASPECT	Autoclave Cure	Filament Winding	Pultrusion	RTM
Temperature distribution and degree of cure	Loos & Springer 1983 Bogetti 1990 Mijoric & Wang 1988 Gutowski et al. 1987	Callius & Springer 1971 Springer 1990	Aylward et al. 1985 Astrom et al. 1991	Bruschke 1992
Resin flow and compaction	Loos & Springer 1983 Gutowski et al. 1987 Dave 1992	Callius & Springer 1971 Tzeng & Loos 1988	Aylward et al. 1985 Dave 1992	Dave 1992 Coulter & Guceri 1988 Bruschke & Advani 1992 Lee et al. 1991
Residual stresses	White & Hahn 1990 Bogetti & Gillespie 1991 Eduljee et al. 1991 Abrams et al. 1987	Spencer 1988		

Table 6.4
State of Modeling in Various Areas of Composites Processing

PROCESS	RATING	COMMENTS
Autoclave Compression Molding		
Thermomechanical models	Good	
Resin flow models	Good	
Post-cure modeling	Fair	Order-of-magnitude estimates rather than estimation of exact microstructural state
RTM		
Preforming	Poor	Time-intensive
Mold filling	Fair	
Cure kinetics & post cure modeling	Fair	
Compression Molding		
Flow	Good	
Fiber orientation	Fair	All models neglect that fiber orientation itself affects rheology of the system
Heat transfer & chemical reaction	Very good	

fabricated by using structural reaction injection molding (SRIM). The model as used has been modified somewhat to integrate specifics related to materials and process details as used by the company. In other cases, companies using simulations for filament winding based their codes on the algorithms developed by Springer et al. at Stanford University. Other codes being used at companies such as JAMCO, KHI, etc. were those given to them as part of subcontracts or joint ventures with U.S. primes in the aerospace arena. However, this should in no way be taken to indicate that there is no development of codes and process models in Japan, and a few examples are given in the next paragraph.

Mitsui Toatsu Chemicals, Inc. uses state-of-the-art simulations for the development of new thermoplastic polyimides and novel carbon-fiber-reinforced thermoplastic composites with high heat resistance levels. The work would seem to rival that conducted at any research facility in the U.S. or across the world. At the Research Institute of Polymers and Textiles (RIPT), there is considerable work being conducted in the areas of injection molding, polymer-metal cluster composites, reaction control, synthesis, and functionalization of self-organizing polymers, and silicon-based polymers. The area of rheology of filled polymeric systems (as related

to injection molding) is being studied by Mitsui Toatsu as well as RIPT, with basic studies being conducted to identify the critical mix for thermoplastic composite development. Mitsubishi Kasei is currently developing an artificial-intelligence-based organic-synthesis design aid in which the chemical structure of the target molecule is input on a graphic terminal, and alternate synthesis routes are processed and evaluated through computer simulation, rather than through experimentation.

MOLECULAR COMPOSITES AND FUNCTIONALLY GRADIENT MATERIALS

Although this term could be used to describe composites formed through the tailoring of interphases, especially through the use of plasma and etching treatments, in this section we refer to the in-situ formation of the reinforcement and matrix through in-situ polymerization. The initial work in this area dates to the early 1970s with the pioneering work of Takayanagi in Japan. The overriding motivation in the formation of such composites is control of microstructure, and hence performance, at the molecular level. These can have low viscosities for ease of mold filling, with improved thermal and moisture resistance and improved mechanical properties, and can take full advantage of the capabilities of composites to act as multi-functional elements. They have the potential for formation of through-the-thickness reinforcement using methods such as injection molding, RTM, and SRIM in the matrix phase. Table 6.5 gives some of the systems under development. A detailed review of work conducted in the U.S., primarily at Wright Patterson Air Force Base (WPAFB), is given in Wiff et al. (1988, 225).

Table 6.5
Review of Important Aspects of Research in the Area of Molecular Composites

METHOD	INVESTIGATION	
Codissolution of rigid & flexible polymers such as BBT in methane sulfonic	Hwang et al. Wiff et al. Wolfe et al.	1983 1987 1981
Dissolving liquid crystalline polymer in the precursor of a coil-like polymer matrix	Kozakiewicz et al. U.S. Patent 4,614,784	1986
Polymerization via a polycondensation reaction in the precursor followed by polymerization of the precursor	Lemke et al. U.S. Patent 5,068,292	1983
PAM polymerization in ε-caprolactam to form PAM/nylon-6	Wiff & Lemke	1992
Copolycondensation	Dotrong et al. Evers et al.	1992 1981

Although attractive, this is still at a very experimental stage in the U.S. but is actively being pursued in Japan. The entire topic of functionally gradient materials is an area of currently high activity at both industrial and government laboratories.

Figure 6.10 presents the basic premise for a functionally gradient material. RIPT, a MITI lab, is conducting research in this area with the participation of industrial scientists from both Japanese and international companies. Currently, the emphasis is on the development of materials with new functions through the control of structure at macroscopic and molecular levels such as through the use of:

- polymer blends
- creation of oriented ultrafine crystal structure
- controlled distribution of fillers, and
- controlled orientation of whiskers and particulates in hybrid composites

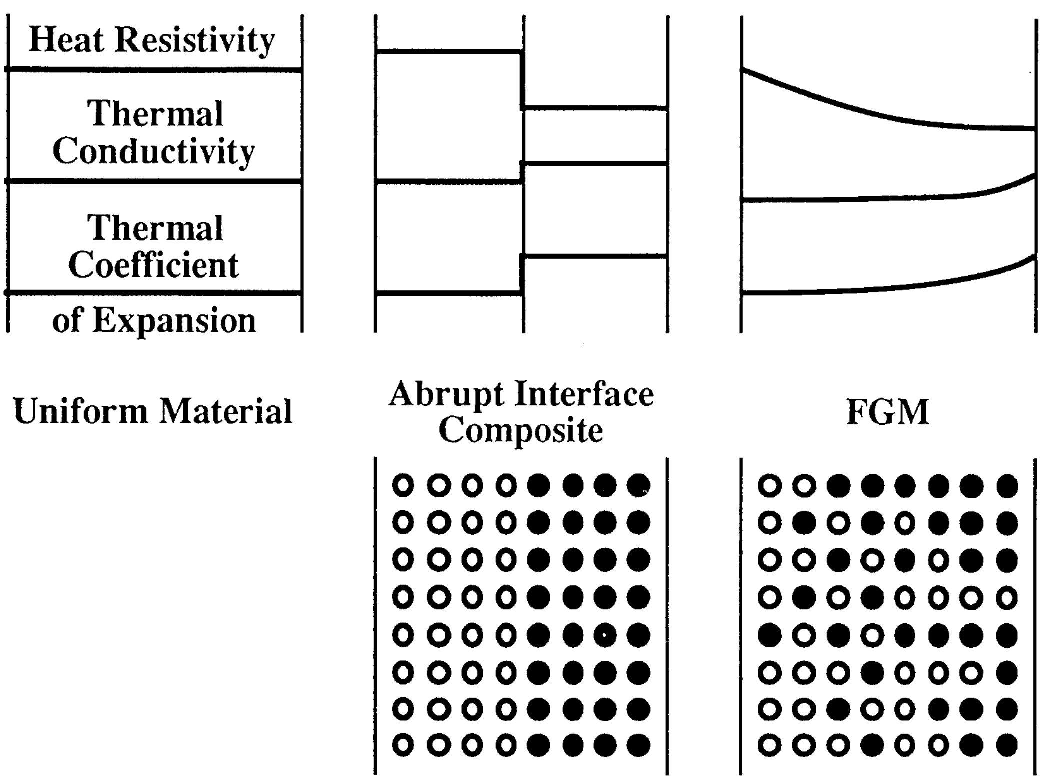


Figure 6.10. Schematic of Functionally Gradient Composites

Scientists at AIST's laboratories are further investigating materials processing technology in this area based on perceived long-range needs. Two projects are specifically worthy of note. In the first, investigators are studying the control of minute structures and composition through the creation of crystals in a reaction field combined with plasma and high-speed ions for composites with high wear resistance on one surface, and good toughness on the other (Fig. 6.11).

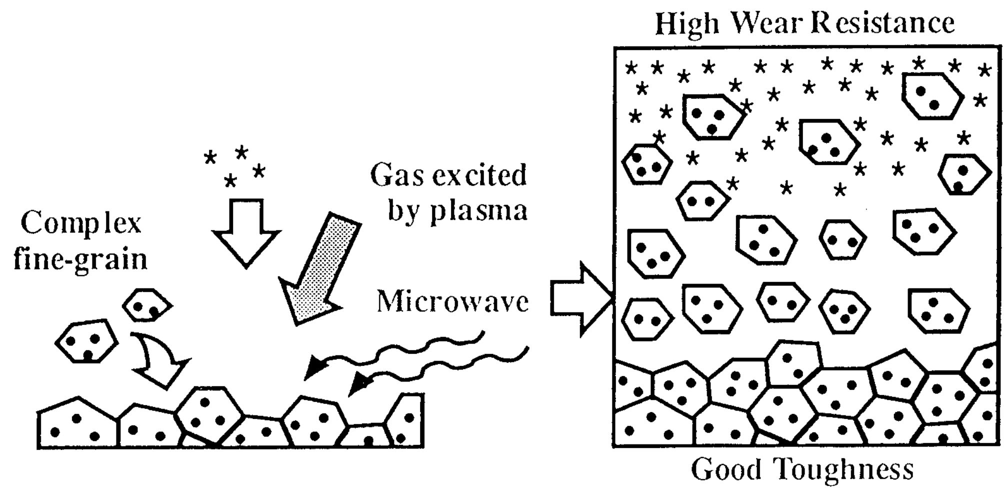


Figure 6.11. Inorganic Material Processing for Tailored Composite Surfaces

In the second, advanced reaction fields are being used to align spin in polymers and thus control blends at the monomer level through the use of photochemical processing (Fig. 6.12). Although this work is currently directed at the polymer level, there is evidence that if it is successful, it will be quickly transitioned into the composites arena as well.

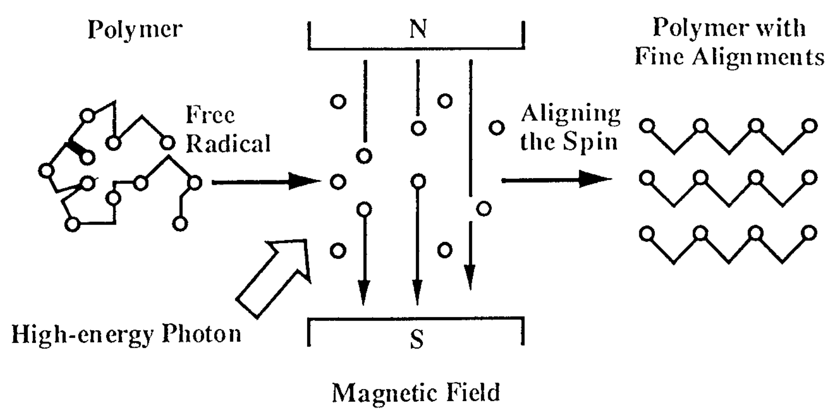


Figure 6.12. Polymer Preparation Using Photo-Chemical Means for Fine Alignment

SENSORS, NDI/E AND QUALITY CONTROL

Sensors, as referenced in this report, refer to devices both intrusive and extrusive that detect or measure physical and/or chemical quantities, and convert measurements from one signal domain into another. Within the realm of manufacturing (or processing) science, the role of sensors is to measure process variables so that they can be controlled in real time or precisely determined for off-line process modification to attain microstructural or chemical compositional goals, and thereby attain performance specification. Most sensors used in the composites area are not developed primarily for this application, and are modifications of those used in the metals and polymer processing area. Sensors for use in composites manufacturing can be classified into four major areas:

- electrical measurements
- wave propagation techniques
- optical and spectroscopic techniques
- magnetic techniques

Electrical measurements include those of capacitance and conductance especially for cure monitoring, and can be directly related to molecular structure and mobility of chains. Several commercial systems, including those from Miomet and Kranbuehl, are already on the market using parallel plate geometry (Mopsik 1984), as well as comb electrode (Sheppard 1981, Kranbuehl 1987), which depend on fringing fields. The outstanding problems today relate to (1) the presence of conductive fibers such as carbon that short out the system, and (2) the selection of the proper measurement frequency to facilitate process monitoring with rapidly curing systems.

Wave propagation techniques are the only mechanical-type tests with the potential for on-line processing. They are, however, widely used at present for post-processing inspection of composite parts. Voids, porosity, fiber volume fraction, viscosity, moduli, glass transition temperature (Tg), degree of cure, etc., can be empirically correlated to wave characteristics. All these tests depend on the generation of an oscillatory disturbance and determination of the propagation characteristics of the wave. Measurement techniques include the use of ultrasonics, interface waves, and wave guide methods. Ultrasonics is the best developed for use in composites as shown in Table 6.6, which relates categories to parameters.

Optical and spectroscopic techniques can directly sense the state of the reactants and hence are of most use in cure monitoring. No commercial systems are currently available, but there exists the potential for the technical barriers to be removed in the near future. Measurement techniques include the use of vibrational spectroscopy, UV visible spectroscopy, and optical fibers. Table 6.7 shows specific techniques within each of these measurement categories.

Table 6.6
Depth of Use of Ultrasonic Techniques

CATEGORY	PARAMETER
Geometry	flaws, delaminations porosity, fiber volume fraction fiber orientation
Material	viscosity mechanical properties degree of cure, gel point glass transition temperature polymer network structure

Table 6.7
Status of Specific Measurement Techniques

MEASUREMENT TECHNIQUE	TYPE	STATUS
Vibrational Spectroscopy	mid-infrared spectroscopy near infrared spectroscopy Raman spectroscopy	- ↑ *
UV Spectroscopy	absorption & fluorescence of visible species fluorescent probes excimer forming probes chemiluminescence	- - - *
Optical Fiber Sensors	fiber attached probers interferometry transmitted light intensity	↑ - *

Key: ↑ increasing * future potential - present

Table 6.8 compares the three basic types of sensing techniques and ranks them in terms of currently available technology. A brief review of non-destructive inspection (NDI) techniques and applicability is given in Table 6.9.

Table 6.8
Ranking of Sensing Techniques

PARAMETER	DIELECTRIC METHODS	WAVE-PROPAGATION METHODS	OPTICAL AND SPECTROSCOPIC METHODS
Response Time	3	2	1
Sampling Volume	2	1	3
Compatibility with Resins	1	2	3
Fiber Compatibility	3	2	1
Temperature Range	2	3	1
Capability for Use in General Manufacture	2	1	3
Sampling Rates	2	3	1

Key: 1 - best 3 - worst

Quality control as related to the Japanese environment and manufacturing science is achieved through the integration of:

- tests on large components (such as the wing-box model)
- use of statistical analysis based on extensive data
- development of NDI techniques
- attention to detailed procedures
- planning for human factors such as in research aimed at the development of new pultrusion and co-curing methods

Although U.S. companies make routine use of non-destructive evaluation (NDE) systems, they seem to be refined to a significant degree in Japan. NDE is considered critical to the success of a manufacturing process by all companies and universities in Japan, and even small laboratories have some level of NDE apparatus. Techniques such as ultrasonic scanning, thermo-mechanical stress analysis, acoustic emission analysis, and X-ray CT scans are used widely, and codes have been developed in-house for image enhancement. In-house development is preferred (such as at the National Aerospace Laboratories) over commercially developed packages, so as to enable attention to detail and greater attention to image

enhancement and speed. Some examples of NDE-related equipment and capabilities present at the National Aerospace Laboratories (NAL) are given in Figures 6.13-6.15.

Table 6.9a
Review of Existing NDE/I Techniques (1)

	RADIOGRAPHY	COMPUTER TOMOGRAPHY	ULTRASONICS	ACOUSTIC EMISSION
Principle/ Characteristic Detected	differential absorption of penetrating radiation	conventional X-ray technology with computer digital processing	changes in acoustic impedance caused by defects	defects in part stressed generate stress waves
Advantages	film provides record of inspection, extensive data base	pinpoint defect location, image display is computer controlled	can penetrate thick materials, can be automated	remote and continuous surveillance
Limitation	expensive, depth of defect not indicated, rad, safety	very expensive, thin wall structure might give problems	water immersion or coplant needed	requires application of stress for defect detection
<u>Defects Detected</u>				
Voids	yes	yes	yes	no
Debonds	yes[1]	yes	yes	yes
Delaminations	yes[1]	yes	yes	yes
Impact Damage	yes[2]	yes[2]	yes	yes
Density Variation	yes	yes	yes	no
Resin Variation	yes	yes	yes	no
Broken Fibers	yes[3]	yes[3]	yes	yes
Fiber	yes	yes	yes	yes
Misalignment	yes	yes	yes	yes
Wrinkles	yes[2]	yes	yes	no
Resin Cracks	yes	yes	yes	no
Porosity	no	yes	yes	no
Cure Variation	yes	yes	yes	yes
Inclusions	no	yes	yes	no
Moisture				

1. Should be physically separated 2. Minor damages may not be detected 3. Might give problems

- Visual/optical techniques can be applied only to surfaces through surface openings or to transparent materials.
- Liquid penetrants technique is applicable only to flaws open to surface, not useful on porous materials.

Table 6.9b
Review of Existing NDI/E Techniques (2)

	ACOUSTO ULTRASONICS	THERMOGRAPHY	OPTICAL HOLOGRAPHY	EDDY CURRENT
Principle/ Characteristic Detected	uses pulsed ultrasound stress wave stimulation	mapping of temperature distribution over the test area	3-D imaging of a diffusely reflecting object	changes in elec. cond. caused by material variations
Advantages	portable, quantitative, automated, graphic imaging	rapid, remote measurement, need not contact part, quantitative	no special surface preparation or coating required	readily automated, moderate cost
Limitation	surface contact, surface geometry critical	poor resolution for thick specimens	vibration-free environment required, heavy base needed	limited to elec. cond., materials, limited to penetration depth
<u>Defects Detected</u>				
Voids	yes	yes[2]	yes	yes
Debonds	yes	yes[2]	yes	yes
Delaminations	yes	yes[2]	yes	yes
Impact Damage	yes	yes[2]	yes	yes
Density Variation	yes	no	no	yes
Resin Variation	yes	no	no	yes
Broken Fibers	yes	no	yes	yes
Fiber	yes	no	no	yes
Misalignment	yes	yes	yes	yes
Wrinkles	yes	yes	yes	yes
Resin Cracks	yes	yes[2]	yes	yes
Porosity	no	no	no	yes
Cure Variation	yes	no	no	yes
Inclusions	yes	yes	yes	yes
Moisture				

1. Should be physically separated 2. Minor damages may not be detected 3. Might give problems

- o Visual/optical techniques can be applied only to surfaces through surface openings or to transparent materials.
- o Liquid penetrants technique is applicable only to flaws open to surface, not useful on porous materials.

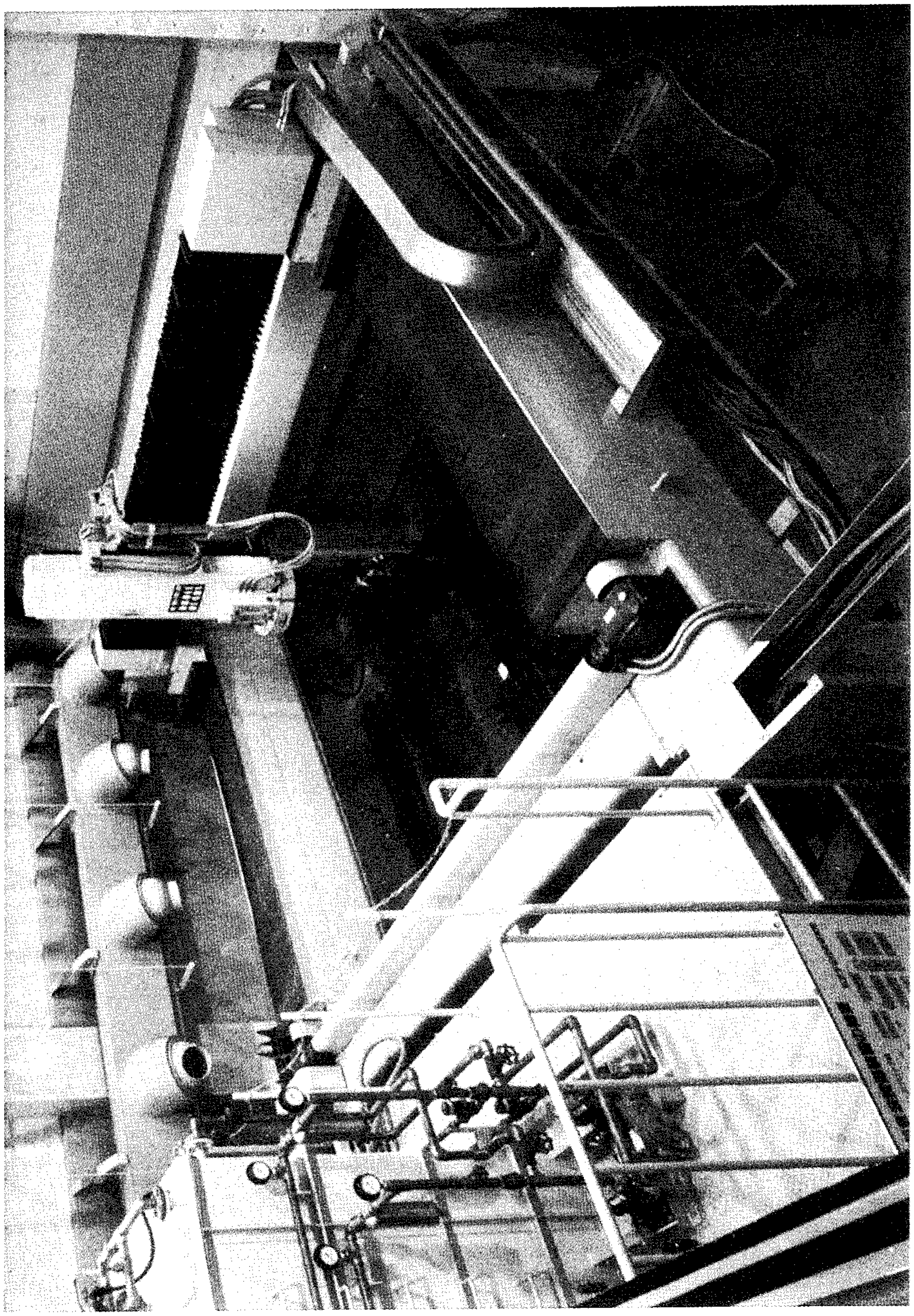
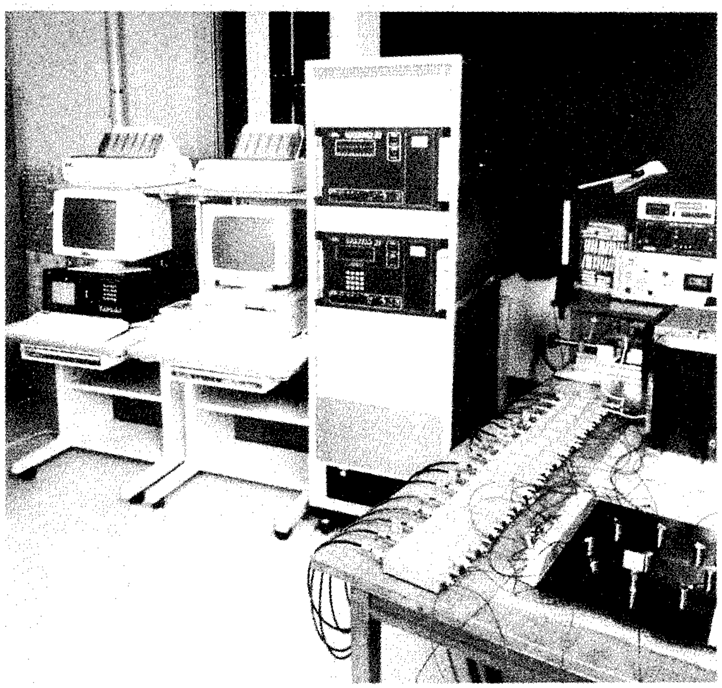
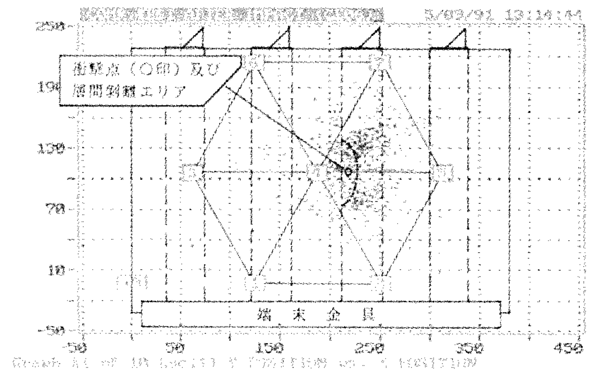


Figure 6.13. Ultrasonic Scanning Tank





結果10
CFRP補強平板の衝撃
後圧縮試験時のAE源位
置標定結果
(赤点がAE源位置)
Results of AE Location
Identification for
Compression Test of
CFRP Stiffened Panels.
(Red dots : AE Source)

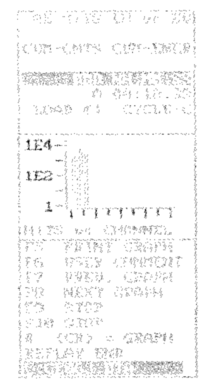
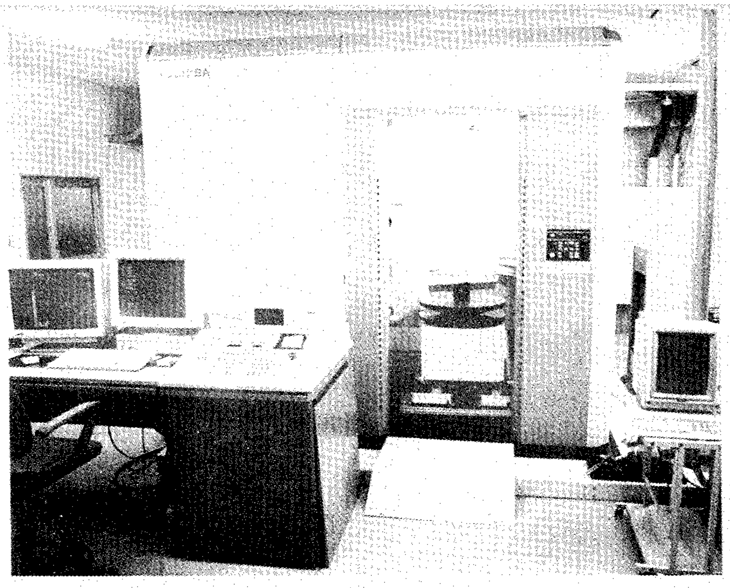
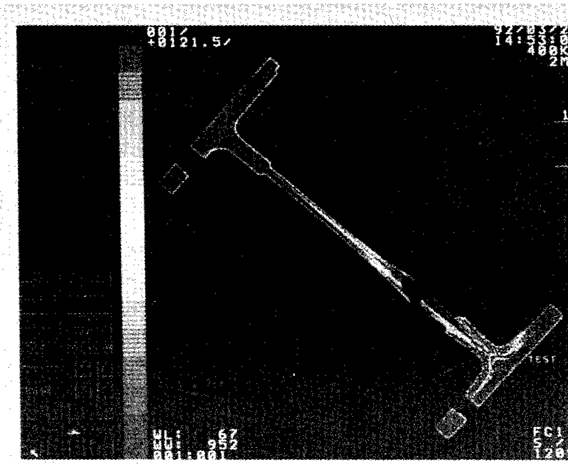


Figure 6.14. Multi-Channel Acoustic Emission Analyzer



システム主要部

Main System.



結果11　CFRP桁破壊後の探傷例

CT Image for Failed CFRP Spar.

主要仕様

被検体寸法：600mmφ×1200mm
画素寸法：150μ
X線管容量：400kV、2mA ファンビーム
検出器数：176ch.

Main Spec.

Object Size : 600mmφ×1200mm
Pct. Element : 150μ
Tube Power : 400kV, 2mA Fan-shaped Beam
No. of Detector : 176ch.

Figure 6.15. X-Ray CT Scanner

Further details on the NDE tools depicted in Figures 6.13-6.15 are given in the trip report for NAL (Appendix C).

Figure 6.16 depicts an overall scheme developed by Professors Kageyama and Kimpara at the University of Tokyo, where again the emphasis is on NDE/I methods.

EXPERT SYSTEMS AND ON-LINE CONTROL

Marginal improvements in the control of composites manufacturing processes, although useful in the short term, will not provide the needed levels of quality, reliability, or economy of production. Lately there has been an increasing emphasis on building quality control into the manufacturing operation (National Materials Advisory Board 1989; Karbhari et al. 1992). The aim of intelligent manufacturing is to use immediate feedback to achieve direct control of product characteristics. The feedback is both to previous steps in the process to adjust control variables, and to subsequent process stages for anticipated changes. Applicable control theories and their relative rankings, as well as their brief descriptions, are given in Table 6.10.

The most advanced work in the area of expert systems and on-line control has been in the area of autoclave cure optimization (some examples of investigators are Abrams, Saliba, Beris). Cure simulation analysis has been coupled to incremental plate theories in order to study the relationships between complex gradients in temperature and degree of cure, so as to enable the use of an expert system linking process modeling and heuristics for on-line control of the cure cycle. Further linking of micromechanics models has enabled correlation of residual stresses, deformation, and fiber undulation to cure state and performance.

In its final state, the optimal system as hypothesized by a team of researchers at the University of Delaware Center for Composite Materials is described schematically in Figure 6.17, wherein process models are used to construct heuristics and rule-based schemas that can be used in the real-time expert system to control the process based on input from sensors.

This is done keeping in mind that the use of process models is computer-intensive in time requirements, and hence it may not be possible to use them on-line to control the process in real time. Future applications of such procedures include the use of expert systems in autoclave processing (Trivisano et al. 1992, 1104), injection molding of composites, pultrusion, and even RTM (Kranbuehl et al. 1992, 907). The closest analog of this system within the Japanese environment is represented by the schematic in Figure 6.16. Although individual aspects of the modules in Figure 6.17 may be at a more advanced stage in Japan, it was not obvious that an integrated structure for intelligent manufacturing as represented above actually existed or was even in use at a primitive level.

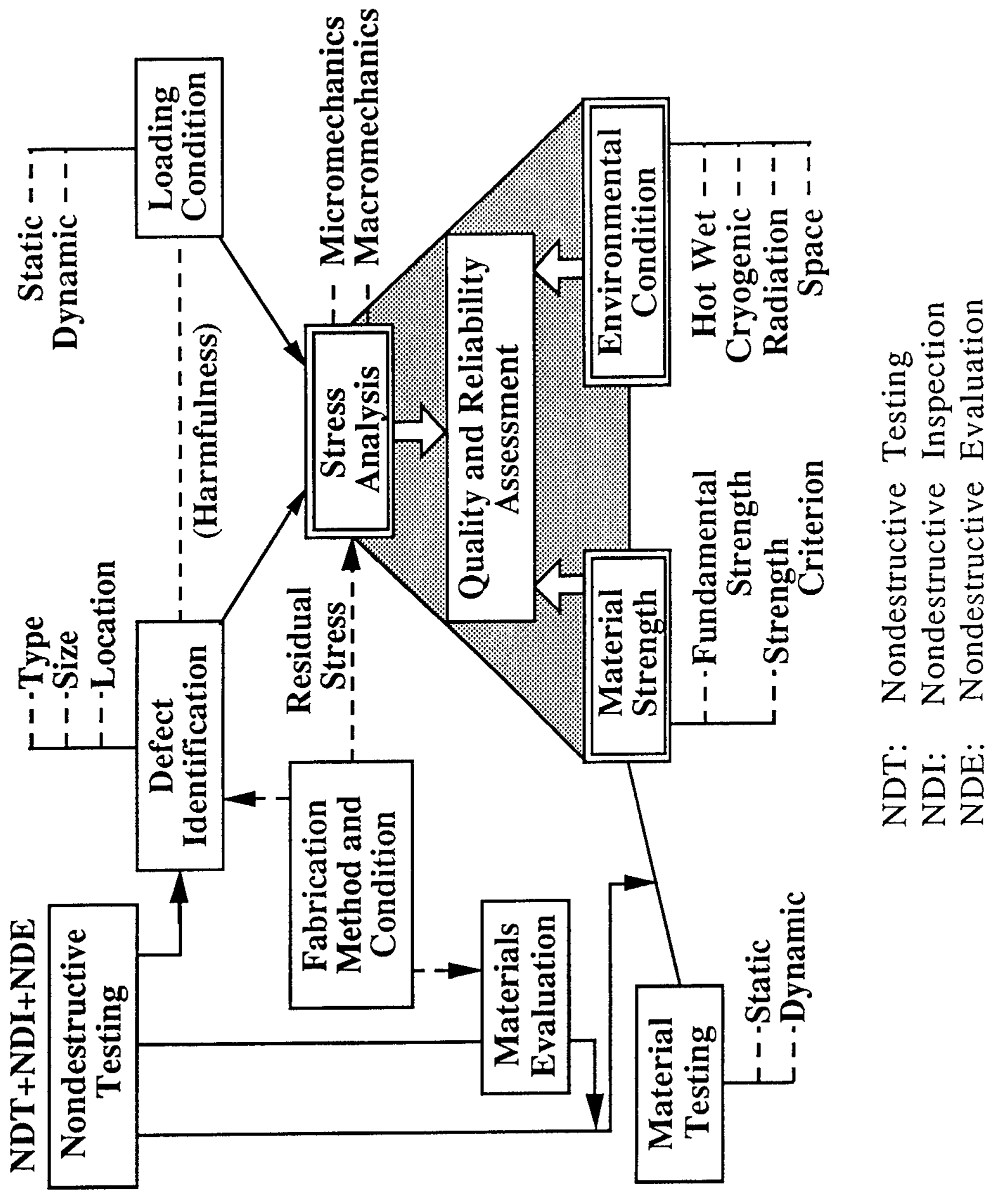


Figure 6.16. A Scheme for Overall Quality and Reliability Assessment

Table 6.10
Ranking of Control Mechanisms

PROCESS CONTROL MECHANISM	DESCRIPTION	RANKING
Feedback Control	Control system reacts to predefined limits.	5
Feed Forward Control	Information is fed to the next step in the process so as to facilitate changes at that level.	4
Intelligent Control	Adaptive control based on sampling	2
Hierarchical Control	Multiple control system for each subprocess	3
Artificial Intelligence	Use of heuristics and real-time control	1

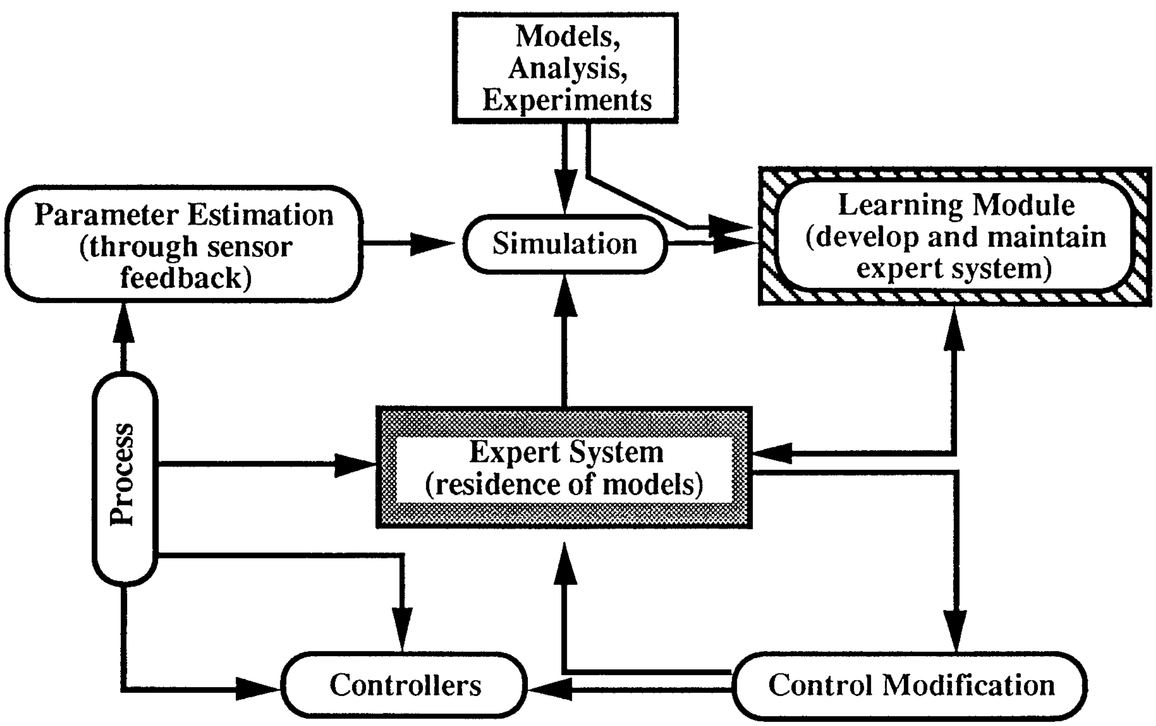


Figure 6.17. Use of AI and Expert Systems for Intelligent Manufacturing

TEXTILE PREFORMING

This area will be treated only cursorily in this chapter because it is the focus of considerable discussion in Chapter 7 (product development), due to the special steps being taken in Japan for its development. It should be noted that, whereas the U.S. composites industry has been largely driven by the predominance of the chemical industry, the Japanese industry is still to a large extent shaped by the textile industry. It is in this area that the Japanese are significantly advanced over their U.S. counterparts, with developments of cost-efficient automated computer-controlled looms for block-type and dome-shaped 3-D construction. Hybrid construction methodologies and methods for the fabrication of hybrid fabric/composite preforms are well advanced. Professor Z. Maekawa (Kyoto Institute of Technology) has conducted a number of advanced studies in the area of simulation and fabrication of 3-D braided structures. These are extremely difficult to visualize, and his computer simulations provide the first steps towards the tailoring of these architectures.

OTHER DEVELOPMENTS

Due to the need for brevity, a number of other developments will not be detailed herein; rather, a listing is provided for the interested reader:

- production of mixed thermoplastic mats using hybrid glass and carbon fiber with a polyamide fiber yarn (Nylon 6, PA) as the matrix
- photochromic liquid crystal polymers
- inclusion-type photochromatic materials
- photosensitive polymers (including laser-sensitive) used for promoting radical polymerization when attached to polymer backbones and used for reduction of thick-section composite cure-related problems
- composite hollow fiber membranes consisting of a polysulfone substrate and coated functional polymer layer
- thermo-responsive polymer gels to be used in smart composites as actuators
- extruded thermo-tropic polyesters and composites
- polymer whiskers (crystals of polyoxymethylene) for use in composites with acoustic applications

- o high-performance matrices using crystals of two-dimensionally cross-linked polymers. These are synthesized by the solid-state polymerization of diacetylene-nylon salts and can be reaction molded to yield composite surfaces with hardnesses exceeding 188±28 (Vickers), i.e. exceeding that of iron.

COST MODELING

A major impediment to the use of composites has been their relatively higher acquisition costs, especially as related to commercial applications. Riggs (1988) has argued that advanced materials such as composites are often not adopted because of a failure to understand the potential cost impacts on the total system. The Office of Technology Assessment has suggested that advanced materials may exhibit lower assembly costs and longer service lives (OTA 1988). The report further argues for the use of a systems approach to cost, and for the use of different cost information systems suitable for the new needs of composites. Table 6.11 shows cost-pertinent responses of an industry-wide survey conducted under the aegis of the U.S. Department of Commerce (1990).

Considerable cost modeling has been conducted at MIT and IBIS using traditional cost-modeling techniques, including a study of the application of automation to composites manufacture (Krolewski 1989). However, these models are specific to special conditions and may not be of generic use for manufacturing. Work is currently being conducted to develop activity-based cost models including the use of stochastics at the Center for Composite Materials to aid in the facilitation of cost as a strategic planning tool. Table 6.12 shows cost economics of the major processes.

Cost models are intrinsically used by the Japanese based on historical data rather than on computer-based simulations. However, it should be noted that the Japanese probably make a sufficient number of prototypes of each part to gather enough cost-related data that can be used to bid, as opposed to U.S. industries which are traditionally funded to the level of only one or two prototypes, making bid-type information almost impossible to obtain.

NATIONAL RESEARCH LABORATORIES

Since a large amount of basic research is conducted or catalyzed by work done at national laboratories (both independently and in collaboration with industry), it may prove useful to give a list of laboratories that work in areas related to manufacturing of polymer-matrix composites. The list is given in Table 6.13 (p. 116), which includes a brief description of the mandate and budget for fiscal 1991.

Table 6.11
Cost Responses

STATEMENT	RESPONDENTS					
	Type of Occupation			Type of Organization		
	Management	Tech.	Non-Tech.	Prod/Cons	Gov't	R&D
The rate at which advanced materials penetrate their potential markets is faster than for traditional markets.	≠	≠	≠	≠	≠	≠
Advanced materials exhibit greater life-cycle costs than traditional materials.	=	≠	≠	≠	≠	=
Future supplies and costs are more uncertain for advanced materials than for traditional materials.	=	=	=	=	=	=
Higher costs of advanced materials are an issue.	+	+	+	+	+	+
The vulnerability of U.S. producers of advanced materials to foreign control of raw materials and/or technology is an issue.	x	x	x	x	+	x
The vulnerability of U.S. consumers of advanced materials to foreign suppliers is an issue.	x	x	x	x	x	x
U.S. competitive disadvantage in commercializing advanced materials is an issue.	+	+	+	+	+	+
There is interest in obtaining information related to economic factors and problems.	=	=	=	=	=	=

Key:

=	Agree
≠	Disagree
+	A major problem
x	A minor problem

Survey Make-up

Management	35%	Producer/Consumer	26%
Technical	35%	Government	20%
Nontechnical	11%	R&D	23%

Source: U.S. Department of Commerce 1990

Table 6.12
Cost Economics of Major Processes

PRODUCTION METHOD	ECONOMIC MINIMUM UNITS	EQUIPMENT COST	TOOLING COST	PRODUCTION RATE
Autoclave Processing	100 - 1,000	Low	Low	High
Compression Molding	1,000 - 10,000	Moderate	Low	High
Filament Winding	100 - 1,000	Moderate	Moderate	Moderate
Injection Molding	10,000 - 10,0000	High	High	High
Layup	100 - 10,000	Low	Low	Low
Pultrusion (unit length)	1,000 - 10,000	High	High	High
RTM	100 - 1,000	Low - Moderate	Low - Moderate	High

SUMMARY

If the U.S. is to maintain its technological lead in the area of advanced composites, it is essential that we continue to build a quantitative knowledge base of fundamental materials and process understanding. Only through such a procedure would it be possible to completely exploit the aspects of composites as identified in the structural hierarchy by McCullough.

Present advances in the use of novel cure mechanisms, including the use of microwaves, electronic beams, nuclear energy forms, and other sources are fast being developed on a research level. Surface modification of fibers through plasma treatment, chemical reaction, and deposition and grafting provide new opportunities for the development of interphasial zones. However, again, most of these developments are at the research level and need a committed effort to take them into commercialization and use in the industry. The true challenge lies in developing a composites product design science that will tie microstructural and processing models to performance criteria and design specification through computer tools.

Table 6.13
National Laboratories Contributing to Composites R&D

NAME	DESCRIPTION (COMPOSITES RELATED ACTIVITIES)	FY '91 BUDGET (¥ million)
National Aerospace Laboratory	Aeronautics and space research	10,600
National Research Institute for Metals	R&D on advanced and synthetic materials, assessment of reliability	6,651
National Institute for Research in Inorganic Materials	Central organization for fundamental research and overall policy (this institute governs university research as well)	480
Mechanical Engineering Laboratory	Mechanics, design, materials and manufacturing	3,471
National Chemical Laboratory for Industry	Technology and standardization	4,658
Government Industrial Research Institute, Osaka	Heat durable materials, surface modification	2,756
Government Industrial Research Institute, Nagoya	Materials and equipment	2,628
Research Institute for Polymers and Textiles	Development of new polymers and composites	1,683
Industrial Products Research Institute	Materials evaluation and sensor technology	1,587
Government Industrial Research Institute, Shikoku	Marine polymers, biodegradable polymers	574
Government Industrial Research Institute, Tohoku	Advanced materials	627
Ship Research Institute	Structures	2,992
Building Research Institute	New materials, fabrication procedures, seismic retrofit	2,470
Institute of Physical and Chemical Research	Functional materials	22,702
Research and Development Corporation of Japan (JRDC)	Industrial sponsorship, cooperative projects	15,755
Japan Information Center for Science and Technology	Information collection and dissemination	13,000
Institute of Research and Innovation	Cooperative research and development	2,674

In summarizing, it is worthwhile to keep in mind the results of a survey conducted by the National Institute of Standards and Technology (NIST) in 1990. Table 6.14 ranks processing methods in order of priority with their raw scores.

Table 6.15 ranks the main processing barriers as noted at that point in time. Although the information is slightly outdated, it is the author's view that the ranking is still correct and represents critical needs in the understanding of manufacturing science for composites.

Based on this and other studies, it is possible to indicate that future trends in potential materials will include composites with liquid crystal polymers and molecular composites (especially as integrated with RTM), smart materials, and functionally gradient materials, all of which are under intense study in Japan.

It may be useful in summarizing to comment briefly on a recent assessment by MITI on Japanese industrial technology. MITI concluded that:

- Conventional industrial products manufactured in Japan are equal to or technologically superior to comparable products throughout the world.

- The technological level of Japan's high-technology products is always improving with a considerable number meeting or surpassing the world standard.

- The level of basic technology research is generally lower than that for manufactured goods, both conventional and high-tech.

This would seem to imply that even the Japanese feel that while they can successfully compete in the area of production, they are lagging in fundamental research. Their developmental methods would thus seem to assure them of a high degree of success using a highly changed form of manufacturing science (i.e., one which is more applied than basic and more integrally linked with the product development system). The focus of their manufacturing science system (such as it is) may be simplified to the schematic shown in Figure 6.18.

The Japanese focus on using existing materials, processes, and technologies to develop new and improved products, with new materials, processes, and technologies being by-products of the creation of new markets. This is in stark contrast to the paradigm often used in the rest of the world, where a product or process is often developed first and then a market identified. However, as will be explained in the next chapter, the Japanese will often see an opportunity for a new market (as in the civil engineering area) and then go about developing it simultaneously with the development of new material forms (for example, grids by Shimizu, and Tow Sheet by Tonen).

Table 6.14
Processing Methods Ranked in Priority as per NIST Survey

PRIORITY RANKING	PROCESSING METHOD	RAW SCORE
1	Pressure Molding	84
2	Liquid Molding	82
3	Filament Winding	39
4	Thermoforming	29
5	Pultrusion	21

Table 6.15
Ranking of Potential Barriers to Processes

PRIORITY RANKING	BARRIERS	SCORE
1	Resin Flow/Fiber Orientation	69
2	Process Monitoring and Control	52
3	Fiber-Matrix Interface	44
4	Data Validation/Test Standards	33
5	Morphology Understanding and Control	28
6	Surface Quality/Dimensional Tolerance	23
7	Heat Flow	21

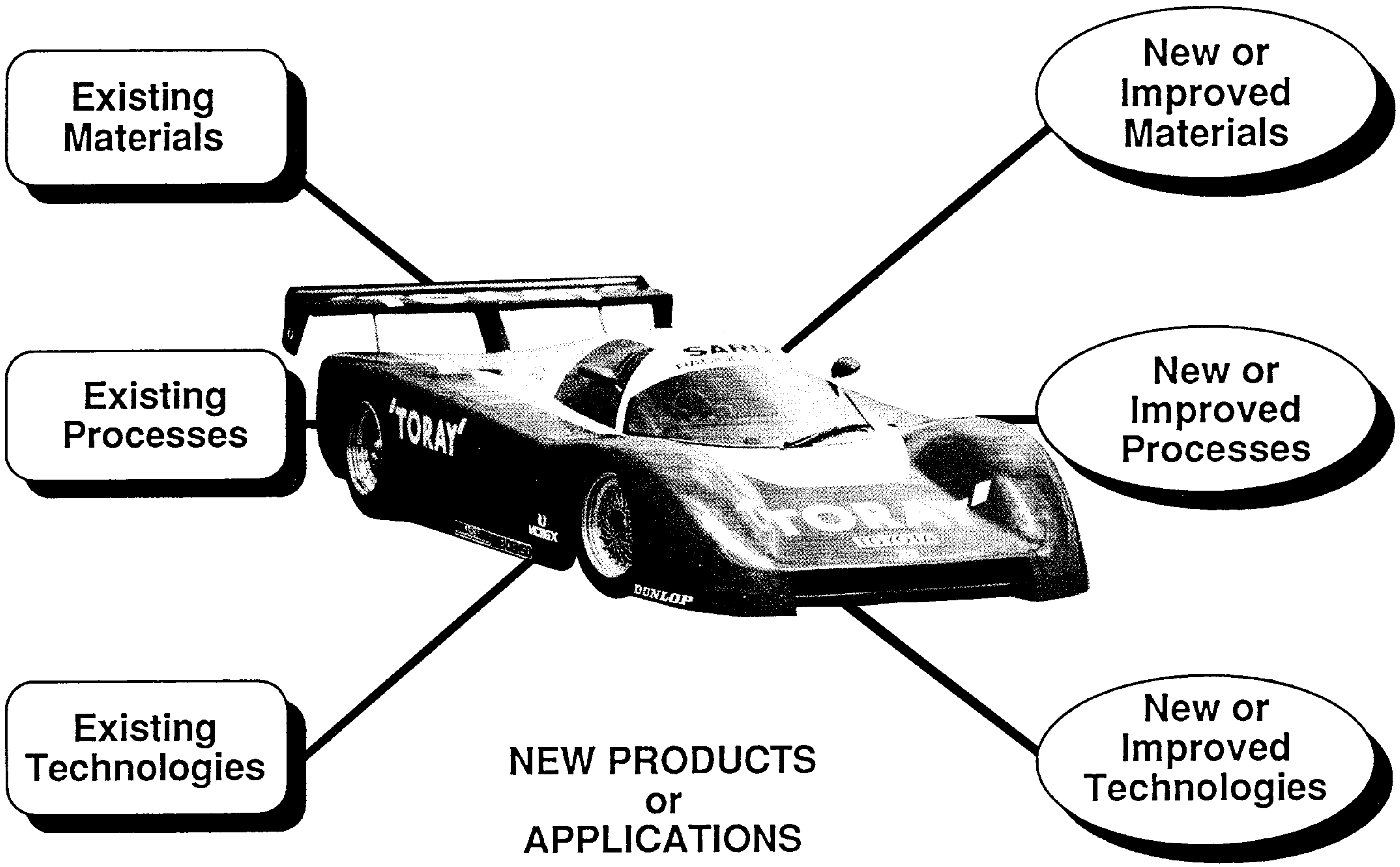


Figure 6.18. The Focus

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CHAPTER 7

PRODUCT AND PROCESS DEVELOPMENT METHODS

V. M. Karbhari

SCOPE OF THE STUDY

Within the limited range of the next few pages, this report attempts to present a snapshot of developments and/or important features in the general area of product and process development. The scope of this section is broad and attempts to address soft as well as hard issues involved in the development of composites. Therefore it will address issues such as design methodologies, rapid market development approaches, people issues, and education. The report attempts to address the features of the product development process through case studies from different areas related to composites. As brought forth in the previous chapter, the underlying premise is that the Japanese do not differentiate between basic manufacturing/processing science and product development. Rather they address the entire area from an applications perspective.

The reader is cautioned that although composites have been in use in the United States for decades, this area remains underdeveloped and our advances are probably shadowed by the advances made in Japan. It must however be mentioned that approaches such as total quality management (TQM) and statistical process control (SPC) following Deming and Juran, although developed in the U.S., found greater acceptance initially in Japan, to the point where they are now used as a "matter-of-fact," and the different facets of "concurrent engineering" are deeply ingrained in the thought and activity processes. At the outset, however, the reader is cautioned against making widespread comparisons between Japanese methodologies and those used in the United States for the purposes of suggesting

broad changes in approach, as many of the differences have their roots in the different socio-politico-cultural systems prevalent in the two countries.

Within the context of this chapter, we will:

- briefly review the methodology considered as optimal for the development of composites -- namely a concurrent engineering based one
- emphasize some basic features emphasized by the Japanese in the development of production systems
- present some case studies illuminating different facets of the product realization process (PRP)
- provide an example of the management structure of one of the companies visited
- provide a brief glimpse into the formation of a precompetitive product development organization
- present some broad overall conclusions of the study

INTRODUCTION

The tailorability of composites for specific applications has been one of its greatest attractions, and simultaneously one of its most perplexing challenges. The wide choice of materials combinations, processing methods and shapes possible, present bewildering problems of selection. In the isotropic world of traditional materials it was possible to use tables, charts, and simple formulae to check the validity of a concept, thereby relegating the need for specialists to the final stages before prototyping. This is not possible in composites, where specialists in different disciplines are needed almost routinely, even at the stages of concept generation. Concurrent engineering thus is an ideal tool for composites product development, to the extent that were it not established in other fields, it would have been invented for composites out of necessity (Wilkins and Karbhari 1991). The economics related with the traditional iterative norm of product development makes it necessary to promote an integrated approach that enables a more direct form of development. Every decision made during the product development process is intricately related to the three interacting decision areas: materials, configuration, and process plan, as shown in Figure 7.1. The concept of linking the attributes of performance, properties, microstructure, and processing has recently been developed as an extension to the notion of the necessity of recognizing design interactions.

Each of the elements in Figure 7.1 presents a spectrum of choices. The configuration of a composite is unique in that it includes both shape and microstructure, any or both of which could be varied to attain a specific attribute. Unlike manufacturing methods for metals, the processes related to the fabrication/manufacture of composites have limitations based on shape,

microstructure, and materials. Theoretically any combination of two or more phases, one being a matrix and the other serving as the reinforcement, can be used as the constituents of a composite. For composites, this has often been regarded as the greatest advantage and simultaneously the most difficult challenge of materials selection. The development of composites is a complex process and requires the simultaneous consideration of various parameters such as component geometry, production volume, reinforcement and matrix types and relative volumes, tooling requirements, and process and market economics. With the increase in complexity of streams of concurrent processes, there is an increased probability of losing control of the key characteristics necessary to add value, hold down costs, and meet customer expectations. The myriad choices available make it imperative that the functions of economics, design, and manufacturing be integrated during the development process.

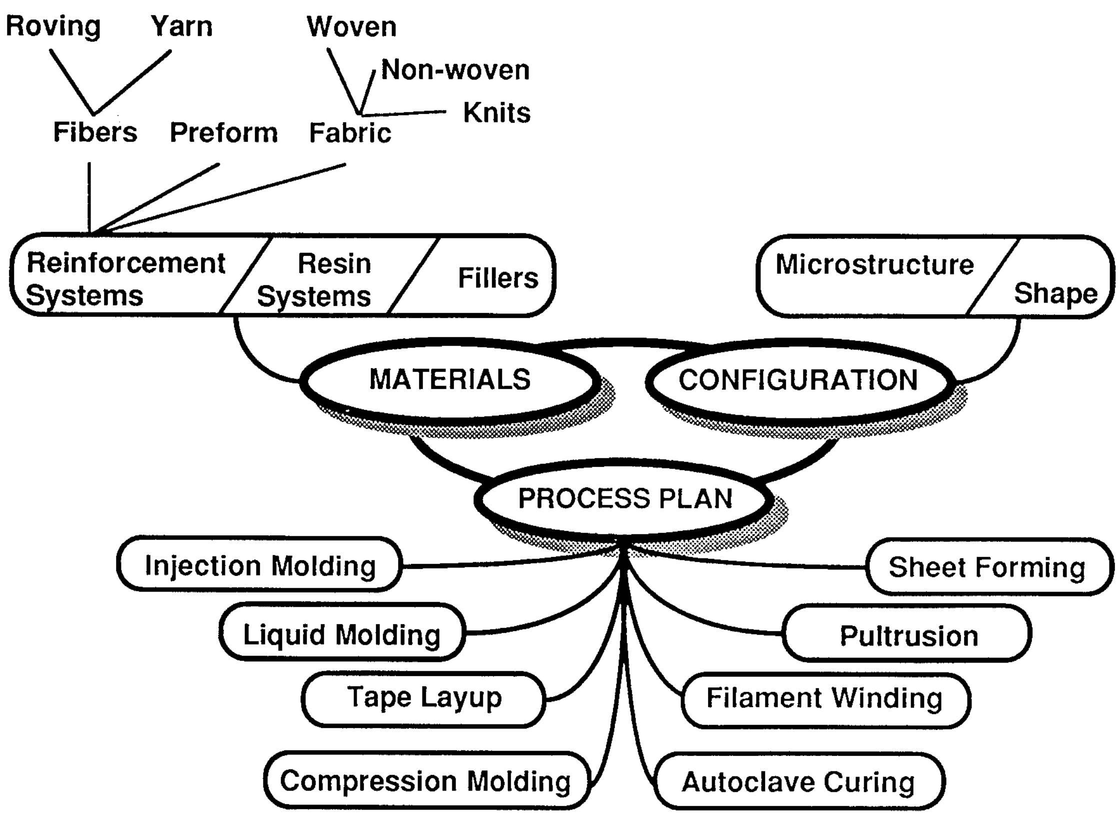


Figure 7.1. Interacting Decision Areas

Our ability to efficiently and competitively manufacture composites depends not only on our embracing new management techniques, but also on our developing a unifying concept of materials-by-design, wherein computer modeling is combined with theory, experiments, and heuristics. In the past, practical remedial actions in the composites test-fix loop have primarily been adapted from the metals paradigm and are often ill-suited to the task. While there remains a need to improve the traditional sequential build-test-fix design methodology for product development, emphasis must shift away from developing remedial actions and towards improving conceptual planning which can enhance responsiveness and realism at earlier stages in the process. Taken to the extreme, prior proper planning should eliminate the need for remedial measures. In any technology, the decisions made early in the product conception stage have deep implications for the subsequent stages in the development cycle. Insofar as the successful development of composites (and the associated structures) are concerned, the facilitation of the efficient selection of aspects from each of the three areas of constituent materials, configuration, and processing, takes on an added dimension of importance, as decisions related to these are locked-in very early in the product design process. The motivation for tools to aid in facilitating the decision-making process is primarily one of economic leveraging, as seen in Figure 7.2.

As is apparent from the figure, the opportunities for development-process-related cost reductions decrease as the design moves along the product realization process (PRP) time-line. Up to 70% of the total life-cycle costs are normally committed at the end of the conceptualization (or preliminary design review) stage. Due to exigencies of economy associated with product development of advanced materials, such as high initial scrap rates, high material costs, and limited reworkability, early decisions are critical and have a major impact on further development. The memory of the high cost of past materials selection errors in the prototyping of composite products has often proved to be a deterrent to their conceptual selection in new programs, especially when in competition with a familiar metals paradigm, which trades off potential customer satisfaction for lower risk. This situation commonly occurs with emergent technologies in fields where the customer-perception derived market forces have remained relatively constant (leading to conservatism), and in which current product paradigms must be displaced to gain market share. In all such cases it is essential that activities critical to the success of the PRP not be omitted during the product development cycle. Recent studies have shown that a minimum number of specified product design management activities must be performed in order to achieve a high success rate with new products or technologies (Cooper and Kleinschmidt 1986; Hise et al. 1989). Obviously, the greater the number of these activities conducted, the higher the probability of success.

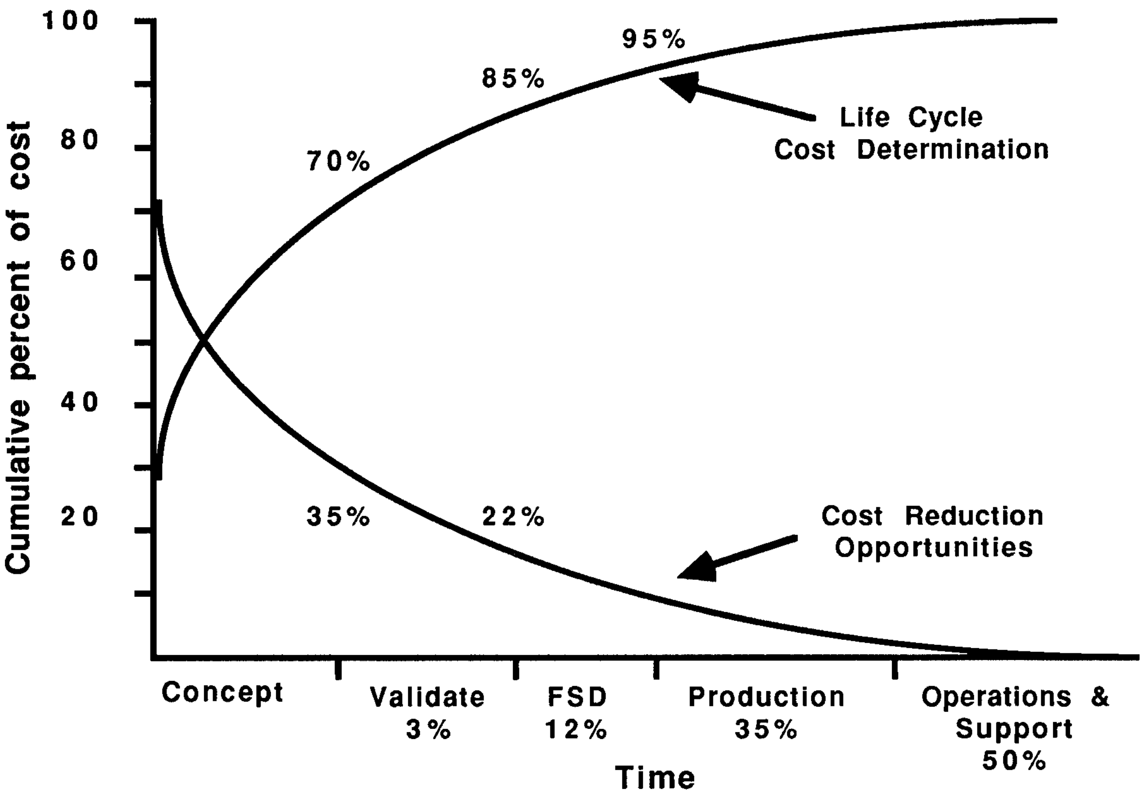


Figure 7.2. Opportunities in Early Design (after Ashton 1991)

DESIGN METHODOLOGIES

While discussing design methodologies, it is important to understand that what is being described is a set of conceptual approaches that are used to develop the product realization process. In light of the coupled decision areas in composites and the need for early design decisions, the design process itself should be thought of as one that stretches from conceptual design to actual process design and fabrication. The methodologies outlined below, with the exception of the total quality design (TQD) process, were however developed for generic use, but have been found to be universally applicable. There are two major schools of thought regarding product development methodologies: (1) the scientific, as represented by Dixon (1988), and (2) the engineering method, as represented by Koen (1985). In the former, prescriptive methodologies are only developed following the development of accurate descriptive methodologies that lead to testable theories of product development. The latter prescribes that the prescriptive methodology be

put forth based on the best available information, and then modified as necessary. Again there is perhaps more evidence of their use in the area of composites in Japan, than there is in the U.S.

Hubka's Methodology (Hubka 1982)

This is also termed the "general procedural model of design engineering," and is a highly structured and detailed model whose main characteristics can be captured in Table 7.1. Although fairly detailed, it is perhaps more useful as a teaching aid than a methodology for composites product development. More than anything else its lack of applicability to composites stems from the fact that it does not focus on the early part of the design process, but concentrates on the later stages, which makes it unable to address the concerns in Figure 7.2. However, it is perhaps this method that is still used most often in composites development.

Cross' Methodology (Cross 1989)

This methodology is very adaptive and actually prescribes little except a set of three rules: (1) adopt a framework; (2) select design methods to flesh out the framework; and (3) continually review and update the framework during the development effort.

Cross suggests that the framework could be made up of six basic steps: (1) clarifying objectives; (2) establishing objectives; (3) setting requirements; (4) generating alternatives; (5) evaluating alternatives; and (6) improving details. The process is thus almost linear and in fact completely leaves out the important aspects of team-customer interactions.

The Total Development Process (Clausing 1988)

Clausing's methodology is more structured and attempts to evaluate each element on the basis of its impact on competitiveness, but it does focus on teamwork and collaboration. The methodology is organized around the following 10 cash drains of product development: (1) technology push, but where's the pull; (2) disregard for the voice of the customer; (3) eureka concept; (4) pretend designs; (5) pampered products; (6) hardware swamps; (7) here's the product -- where's the factory; (8) we've always made it that way; (9) inspection; and (10) give me my targets -- let me do my thing.

Clausing further prescribes the use of Pugh's concept selection method (Pugh 1981) and the House of Quality (Hauser 1988) as tools to be used. Although a very useful and illuminating methodology, it lacks the tools for actual application.

Table 7.1
Summary of the General Procedural Model

STEP	1	2	3	4	5	6
ENTRANCE	Problem Assignment	Design Specification	Functional Structure	Concept Sketch	Layout Sketch	Dimensional Layout
EXIT	Set of Requirements	Abstract Representation	Abstract, Incomplete Structure	Rough Dimensional Description	Complete Description of Nearly All Features	Complete Description of All Features
DOCUMENT	Design Specification	Functional Structure Diagram	Concept Sketch	Layout Sketch	Dimensional Layout	Shop Drawings, CAD/CAM Aids
OBJECTIVE	Complete Basis for Task	"Largely" Optimal Set of Duties	Rough Structure that Realizes Optimal Mode	Add Important Dimensions	Complete Description of Manufacture	Finalized Description of Manufacture
METHODS	Market Research, Checklists, Question-naires	Abstraction, Black Box Technical Process	Morphology Matrix Catalogue of Effects	Variations of Charact'ristics Value Analysis	Value Analysis	None Specific

QFD Methodology

Developed initially by Akao in Japan in 1966, quality function deployment (QFD) provides a formal structure for ensuring that customer wants and needs are carefully heard, and then directly translated into a company's requirements for a product as shown in Figure 7.3.

The QFD process maps customer driven requirements to technical requirements, allowing competitive evaluation and weighing of factors to achieve a technical evaluation. The process was developed to this level by Bob King (1988) and further used by Clausing.

Total Quality Design

Developed at the Center for Composite Materials at the University of Delaware, this methodology attempts to synthesize the best of the other methodologies with an emphasis on hearing the voice of the customer and developing design interactions early in the design process. The methodology consists of five main elements described in Figure 7.4.

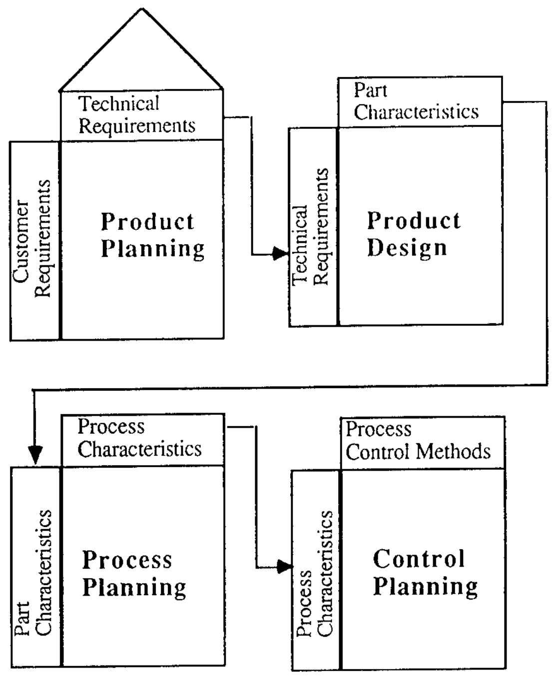


Figure 7.3. The Four-Phase Approach to QFD

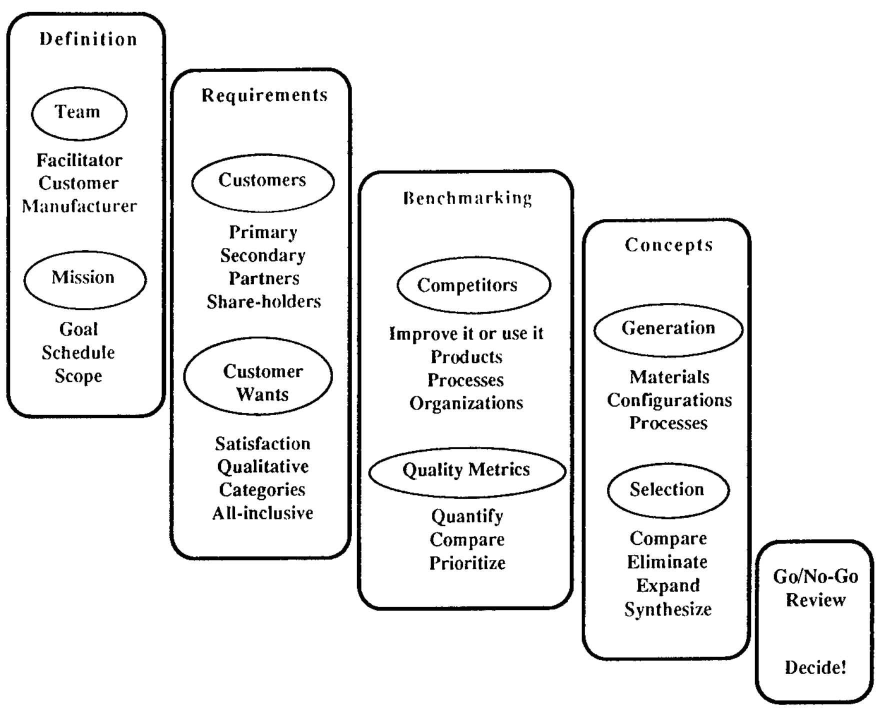


Figure 7.4. The Elements of the TQD Process

The use of these elements allows for organizational flexibility, a clear management vision, and an integrated implementation plan. Most importantly, it provides a framework for the integration of the functional disciplines of economics, design, and manufacturing towards a common goal of composites product development. In order to facilitate the easy use of this methodology, a set of Macintosh-based spreadsheets have been developed to organize the process of conceptual development of products. These are analogous to the House of Quality matrices in which the "Hows" of one stage in development are broken up into clarifying "whats" of the next stage (Hauser and Clausing 1988). The schematic in Figure 7.5 shows the link between each of the spreadsheet based TQD programs, and the links to other activities that must be conducted simultaneously, such as concept generation. The templates serve as facilitators for the integration of the various disciplines, as well as an electronic record of decisions made and the reasoning behind each decision.

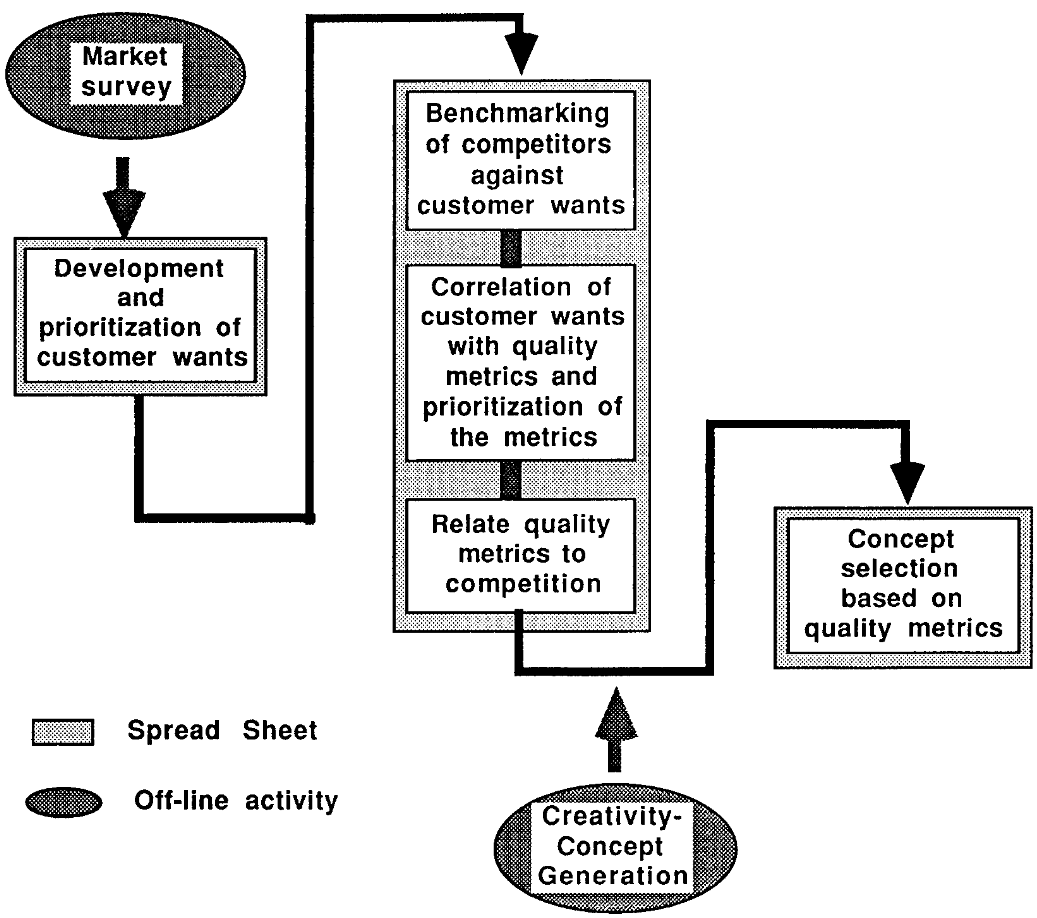


Figure 7.5. Schematic of Use of TQD Templates

Concurrent Engineering

Winner et al. define concurrent engineering as:

> a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements. (Winner 1988)

In the context of this paper, the term concurrent engineering is then taken to represent the approach of collaborative product development with input from each functional group involved in the product development process. The approach taken herein is to include as many tools as necessary, which may include the methodologies mentioned above. The need for the use of a number of methodologies is due to the fact that no single methodology addresses all the concerns for successful product development. A snapshot of this diversity is provided through a comparison made by Henshaw (1989) of the methodologies based on a number of key factors as needed in composites product development (Table 7.2).

A test bed for the use of the concurrent engineering approach through software integration has been established at University of West Virginia at the Concurrent Engineering Research Center (CERC). A major component is a demonstration bed of the use of concurrent engineering for the development of metal-matrix composite (MMC) components for aircraft. An extensive list of 26 tools usable for concurrent engineering is given by Pennell and Akin (1990) and hence will not be repeated herein. Further discussion of case studies and frequency of the use of formal methods (including design of experiments, pareto charts and QFD) is given in the IDA report by Winner et al. (1988) and is not included herein since it contains no breakup to show the actual extent of use by the composites community. It is however known that the DoD routinely attempts to use some form of concurrent engineering and TQM for its own composites projects. It is also being used in the Composite Armored Vehicle (CAV) project.

DESIGN, SUPPORT SYSTEMS, CAD/CAM/CIM

It is difficult, if not impossible, to review all developments in the short space afforded here and within the scope of this document. Therefore attention will be paid to needs, novel approaches, and data rather than on actual procedures. It is also envisioned that actual CAD/CAM/CIM procedures for the aerospace/automotive sectors will be covered in the write-ups of their respective areas.

Table 7.2
Current Ability of Alternative Concepts to Provide Customer Wants

	HUBKA'S METHOD	CROSS' METHOD	QFD (King)	TQM	TQD (Clausing)	TQD
List of Rules	3	1	4	4	1	5
Universality	2	4	4	4	4	4
Covers All Activities	1	2	4	4	4	4
Team Methods	1	1	2	4	1	4
Readability	4	2	4	4	3	2
Integration of Activities	1	3	5	5	4	5
Details Methods	3	1	5	5	2	5
Framework	1	4	2	4	4	4
Product Intent	2	3	5	5	5	5

Design has been defined in a variety of ways. While some have argued for a global definition of engineering design as the information needed to create, use, and dispose of an artifact, in practice the term design is often used in a very narrow sense. Rather than integrating activities as it should, design unfortunately often segregates such activities as product definition, function derived structural specifications, interaction with customers, and planning in the areas of processing, maintenance, and product disposal. It is in the need for integration of these activities that the design of composite structures differs from that of structures fabricated of other materials. With metals, the technology is itself engineered into the basic stock since the properties in many cases do not change much as the result of the fabrication procedure. With composites, however, properties and performance depend not only on the raw materials, but also critically on how the materials, both individually and as a composite, are processed. This mandates consideration of manufacturing in the design phase. Optimum design with composites can necessitate the design of the material not only from the structural viewpoint, but from the matrix impregnation and infusion aspects as well. An illuminating example of this is in resin transfer molding (RTM). The preform is usually designed from a structural point of view, exemplifying its use as the skeleton for the final part. Often, ease of manufacture will even be considered part of the design profile for the preform. However, it is often forgotten that the same preform must also be designed from the

view of infusion, so as to ensure uniform infusion of the resin and proper wet-out of the reinforcement. The same anisotropy that comes from the use of unidirectional and specialty fabrics in order to fulfill strength and stiffness criteria can create directional flow, causing the preform to wet-out primarily in one direction, leaving dry spots in the other. Obviously, there is a critical need for the use of simultaneous or concurrent design for composites.

Traditional designers dealt almost exclusively with the shape of their product. With composites, shape and microstructure are intertwined. Pultrusion, for example, is limited to parts of constant cross-section. Reinforcement microstructures are limited by the process itself, with about 20-25% of the fibers being forced in the axial direction to give the material sufficient strength to withstand frictional forces while being pulled through the die. Filament winding is another process restricted both in the shapes and in the microstructural orientations possible. For composites, microstructure typically refers to the dimensions (length and diameter for fibers), volume fractions, and orientations (with respect to local and global coordinates) of the reinforcement phase in the matrix material. The microstructure of a composite determines to a large degree its performance in terms of mechanical, physical, environmental, economic, and other properties. Most aspects of the microstructure are usually created as the part is being formed into its final shape. It is the inherent scale present in the composite itself that presents both difficulties in analysis and prediction of properties, and also presents opportunities for optimizing performance through changes in the relevant dimensions of the microstructure (Fig. 7.6).

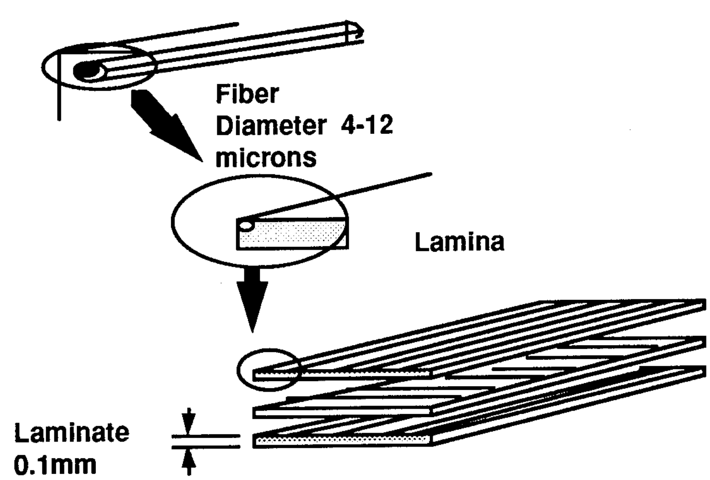


Figure 7.6. Inherent Levels of Scale in a Composite -- Opportunities for Design

A series of recent papers (Karbhari and Wilkins 1990, 1991a, 1991b, 1992a) points out the importance of the scale effect at the microstructural level on design, and the interested reader is referred to these for further explanation. It is increasingly becoming possible to build a tailored skeleton in near-net-shape before the actual fabrication of the composite (achieved through the process of resin infusion through the preform). Similar techniques are being developed for MMCs and ceramic-matrix composites (CMCs), thereby making possible the development of "materials-by-design," not merely at a global, structural level, but also at a local, microstructural level. The development of computer based design selection tools is critical to the development of a true CAD base which leaves the designer with the flexibility of choosing materials, configuration, and process, based on the specific needs of the product. The aspects of benchmarking have recently been applied to such a development in the form of a decision support system. The basis of the current approach is in the fact that the problem of selecting an alternative to satisfy multiple criteria is far easier if approached from a deselection, or discrimination, point of view. The object of the exercise then changes from one of selecting the best alternative to one aimed at rejecting alternatives that would not meet the broad limit of specifications. The easiest method of doing this is through the cross-plotting of attributes as in Figure 7.7, and rejecting those concepts that do not fall within specified bounds that signify the range of the demand profile.

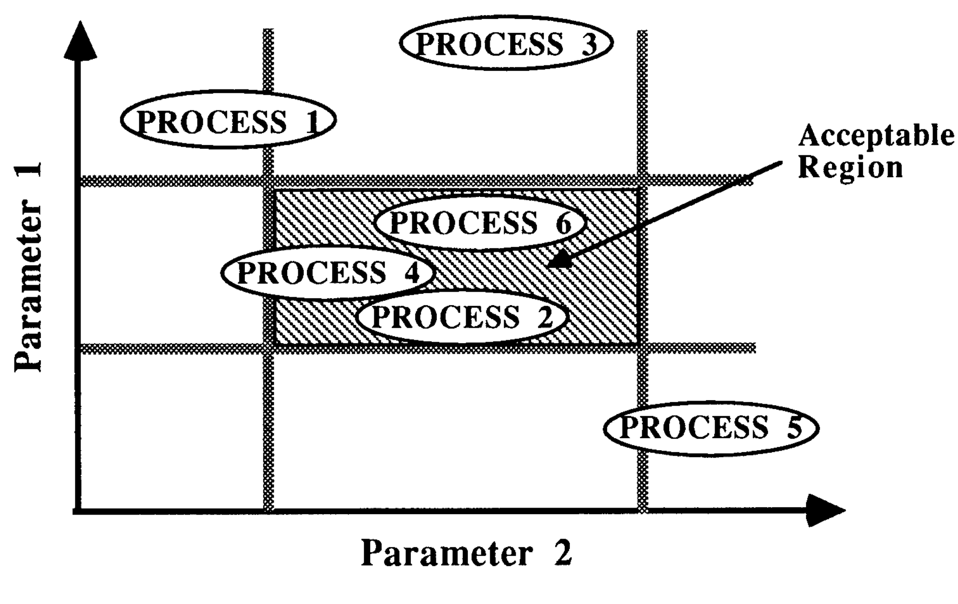


Figure 7.7. Cross-Plotting of Attributes

It can clearly be seen that processes 1, 3, and 5 fall outside the acceptable bounds of the demand profile as set through parameters 1 and 2, and hence can be rejected. The deletion of these reduces the further analysis to a smaller number of concepts, making it both easier to handle their selection, as well as making it cheaper in terms of time and money expended on the process.

Discrimination between close calls would then involve more detailed analysis, and in the case of actual design alternatives, it would be feasible to conduct a more thorough investigation of the remaining few concepts. In the case of structures, a full scale finite element analysis could be run on the few remaining analyses, rather than on all the concepts generated by the team, thus providing for a more efficient and economical use of time and funds. Through the use of such decision support system (DSS) tools it is possible to make efficient use of facilities and budgets. A key ingredient in the deselection process is the representation of knowledge such that discrimination becomes an automatic process. The choice of discriminators is thus of great importance and forms the basis for the DSS (Karbhari and Wilkins 1992b). Figure 7.8 depicts an example of the discrimination of primary processes based on the metrics of shape complexity and microstructural control.

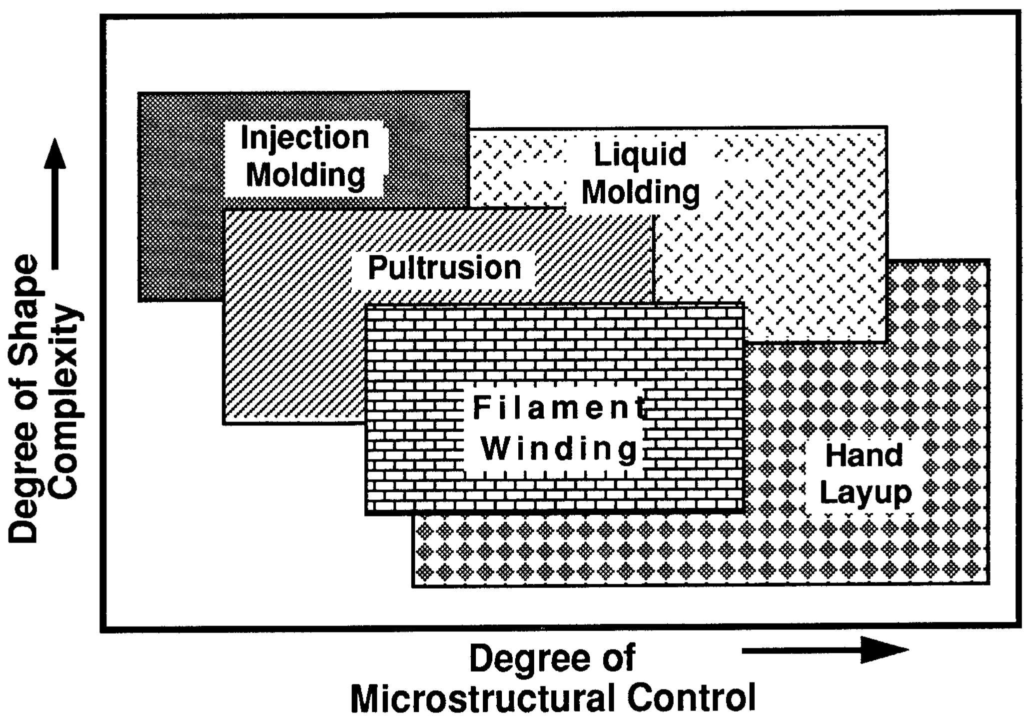


Figure 7.8. Deselection of Primary Processes

A similar scheme is also applied to the selection (or rather deselection) of forming processes based on the attributes of geometric complexity and size (Fig. 7.9). The graphic pertains to the use of sheet-forming processes after the selection of continuous fiber reinforced thermoplastic prepreg tape (APC-2 in this case) was already made.

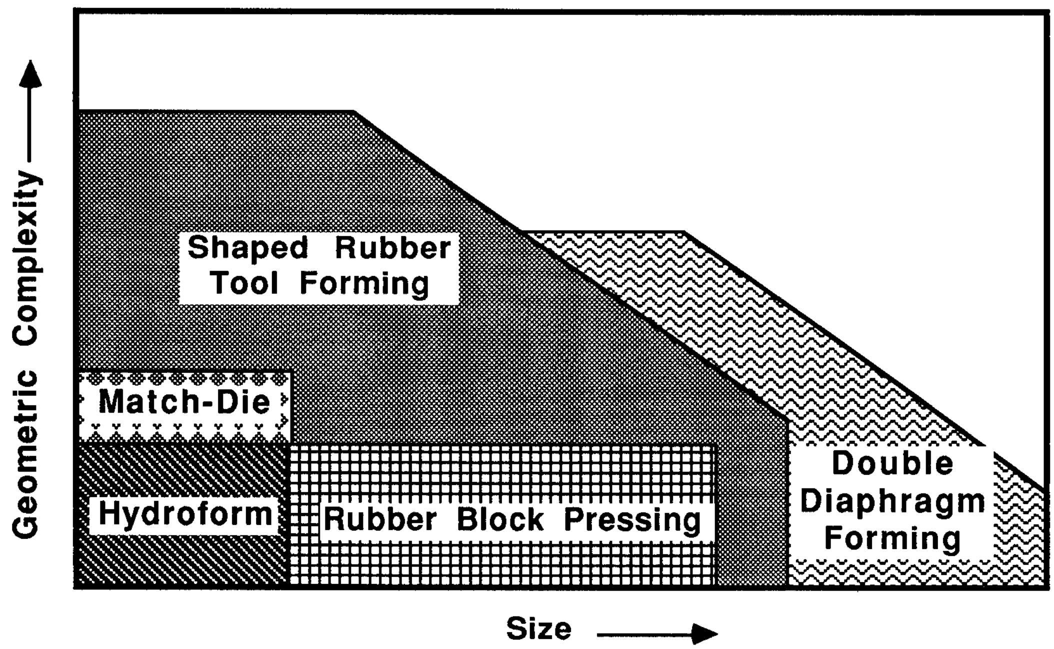


Figure 7.9. Relative Applicability of Forming Processes

Thus the primary material form had been selected, and Figure 7.9 is merely the next step in the discrimination phase of design. For the efficient selection of concepts (whether they are related to materials or processes), it is useful to be able to view data in terms of a set of pairwise comparisons. Obviously it is of considerable interest to view the options simultaneously so as to be able to determine the optimum choices based on a number of criteria. A schematic of this is shown in Figure 7.10 for the selection of fibers. Criteria such as shear moduli, tensile moduli, and coefficient of thermal expansion are compared to the fiber strength; whereas strength, cost, and diameter can be compared in relation to each other as against the coefficient of thermal expansion. Such a scheme lends flexibility to the materials-process selection stage, allowing the user or design team the luxury of simultaneously reviewing the performance of a number of options based on a variety of criteria.

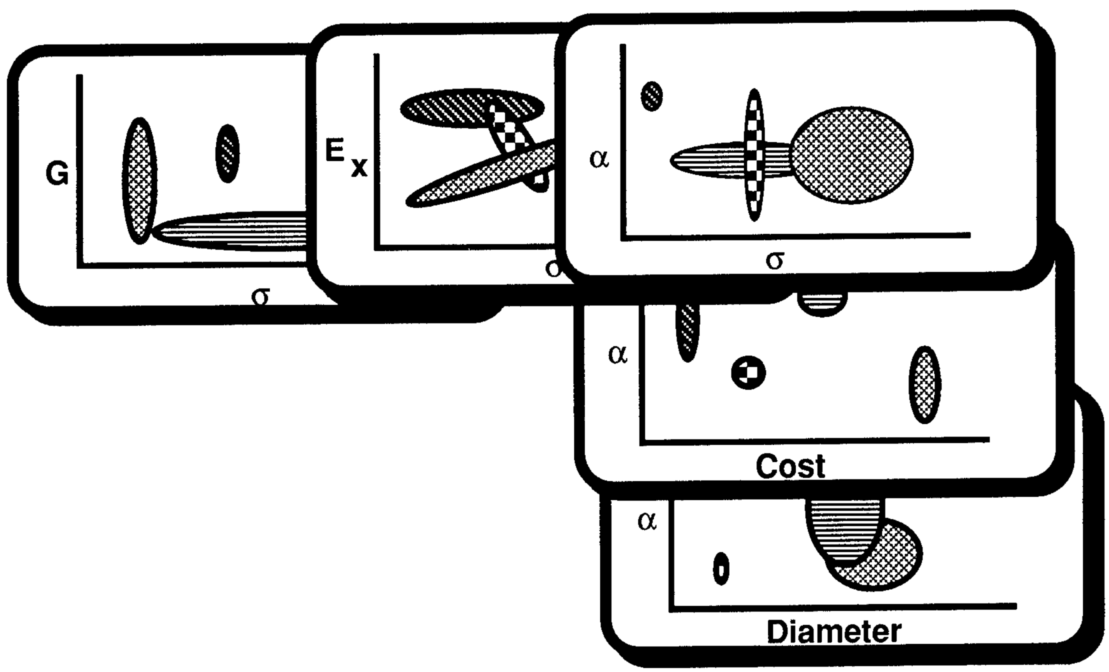
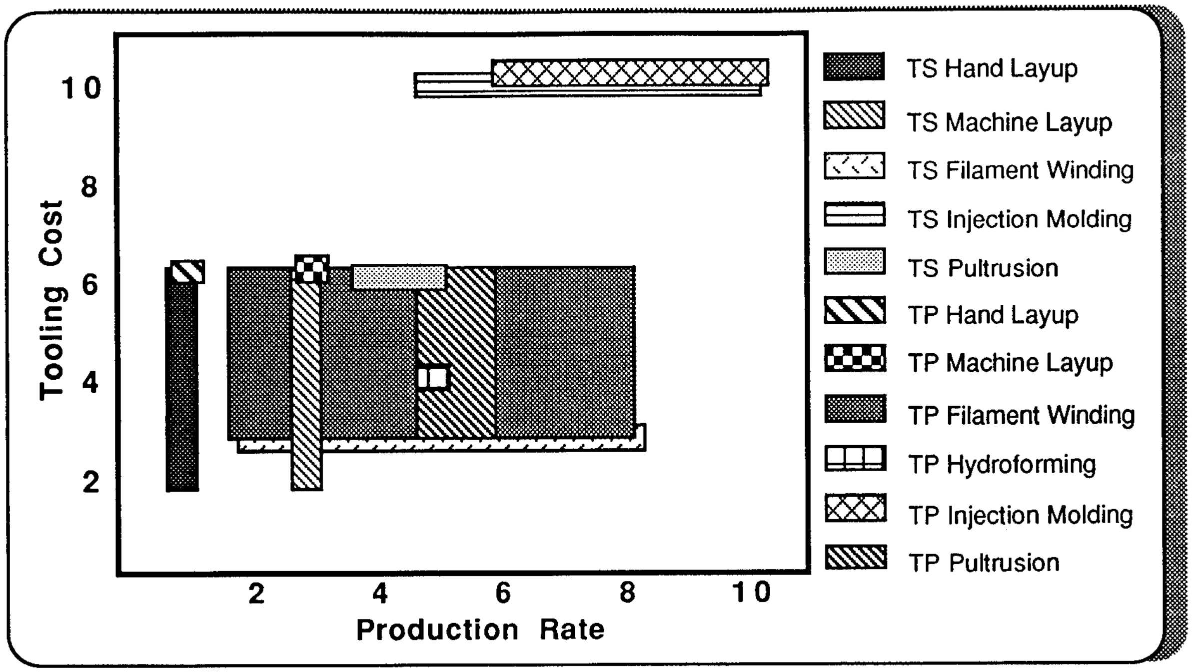
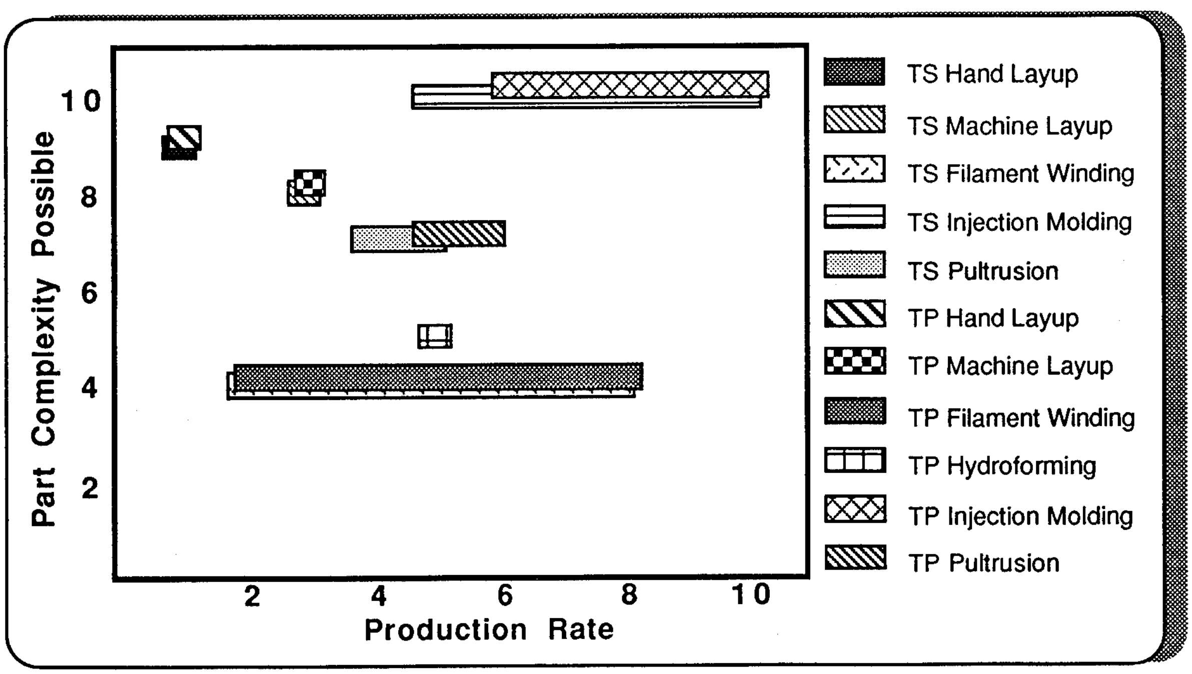


Figure 7.10. Deselection as a Part of CAD

Figures 7.11a-d present the cross-plotting of processes based on five selection criteria. In all these, the letters "TS" stand for "thermoset" and "TP" for "thermoplastic." The criteria of tooling cost, part complexity, repeatability, and level of waste are plotted against a common metric, i.e., production rate. These are among the metrics which are not as readily quantifiable as others, such as cycle time and pressure. However, they are often better discriminators. They also are primarily used as production and/or economic criteria on the basis of which a specific process would be selected. Obviously, the rankings are heuristic and based on judgement, but they do serve as guides for the engineer or design team. For the basis of comparison the processes were ranked on a 1-10 scale with 1 subjectively being the lowest and 10 the highest or best. As an example, under tooling (Fig. 7.11a), 1 would represent no need for tooling, whereas 10 would represent the equivalent cost of a tool for injection molding. Similarly a level of 1 in Figure 7.11b represents the complexity of a flat plate, whereas 10 would be representative of an integrated three dimensional structure. The level of waste reuse is an indicator of the efficiency of usage of the material systems in a specific process. A level of 10 represents a process in which almost all waste is reusable, whereas a level of 1 represents a process wherein the product quality would be such that rework and/or a high rejection rate is a normal fear.

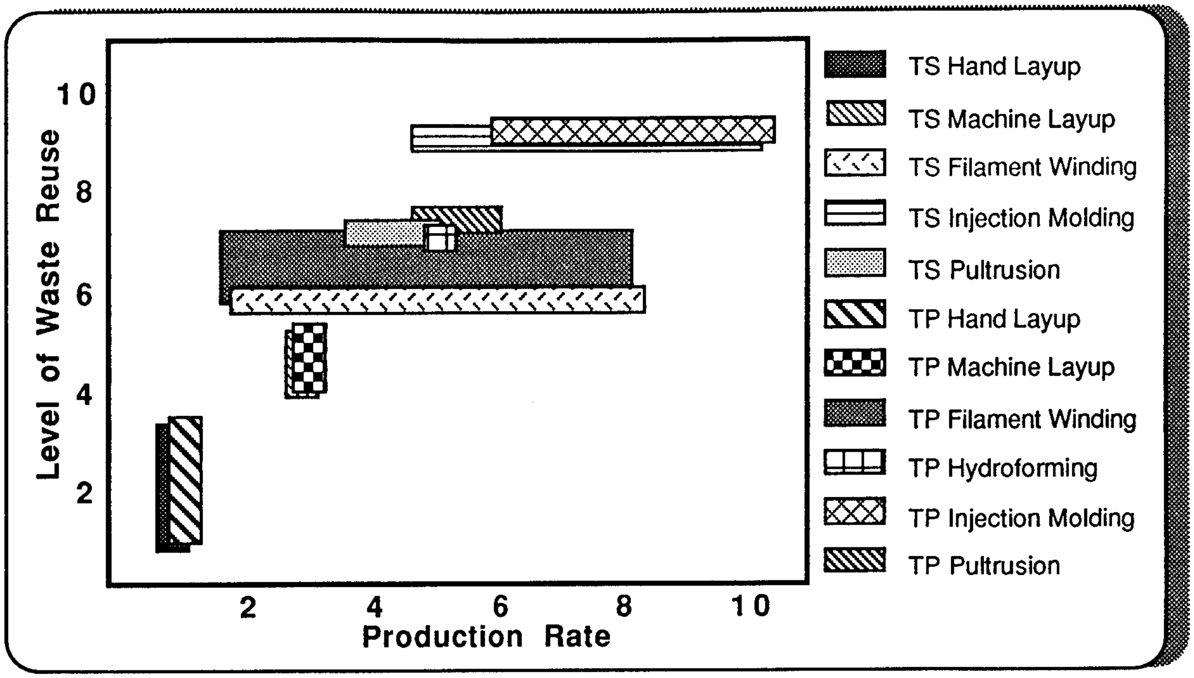


(a)

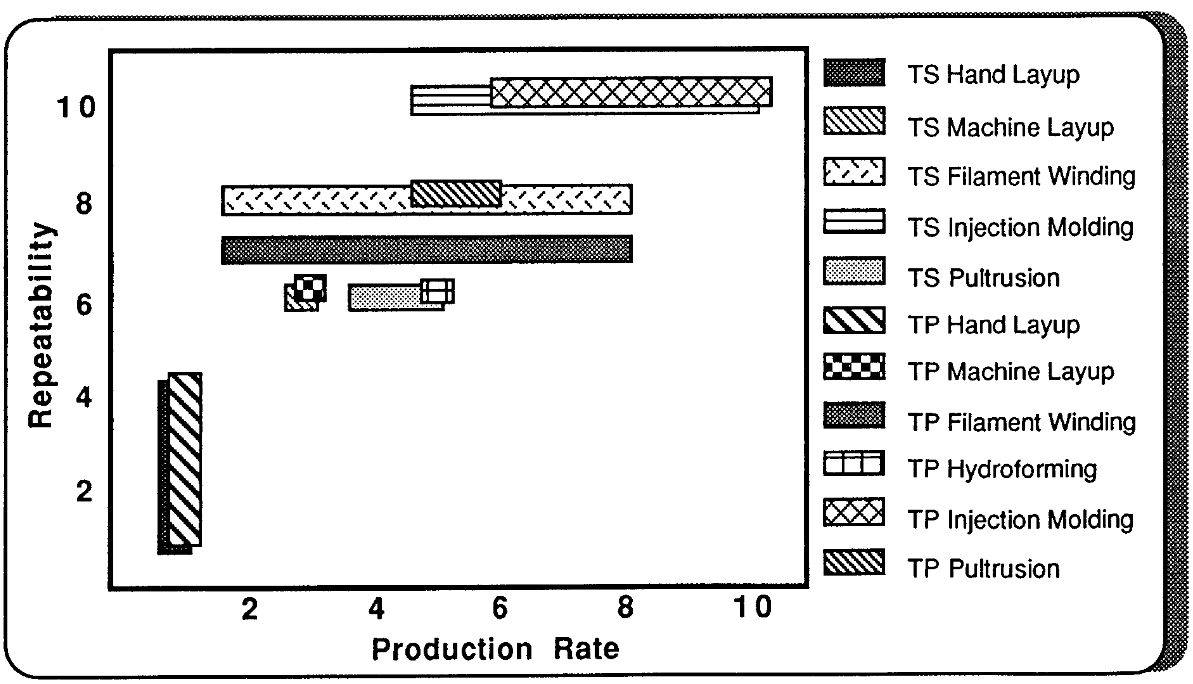


(b)

Figure 7.11a-b. CAD-Based Discrimination (1 & 2)



(c)



(d)

Figure 7.11c-d. CAD Based Discrimination (3 & 4)

Based on these four figures, it is possible for the design team to arrive at conclusions in regard to deselecting (i.e., dropping from consideration) a number of non-viable processes very early in the design stage. This not only saves time and money, but also allows the designer (or design team) to focus on the really important and viable concepts. The visual process also provides a tool whereby it is possible to justify why a concept was dropped or to specify the lack of performance based on specific criteria by the rejected concept. This is not possible in a traditional computer based materials and/or process selection scheme, where deselection is done on the basis of preset and very rigid bounds. This has often led to the exclusion of a concept merely on the basis of its having failed the bound test by a fraction of a percent, even though its performance with regard to other key selection criteria was exemplary. When such a system is linked to a CAD station with facilities for 3-D modeling, feature-based representation, and system representation, true CAD of composites will be possible. The development of materials databases and interchange has been investigated by Sargent (1990) and the interested reader is referred to that publication for further details.

The fabrication of composite structures and products is evolving from labor intensive hand layup methods to automated manufacturing using tape layup, fiber placement, RTM, diaphragm and thermal forming, and other potentially cost effective fabrication procedures. Now, more than ever before, processing costs and problems of repeatability can stall new composite programs right at the profit line. Innovations such as automated methods for laying tape to contoured tools with close conformance have reduced hand labor by about 69%, whereas other developments in automated preform fabrication, as well as the integration of the preform fabrication and molding stages, promise to make an already attractive technology (RTM) even more desirable from the standpoint of economics and productivity. Improvements in process models and controls have resulted in newer methods of monitoring cure conditions, optimizing process cycles, and predicting microstructural changes based on processing conditions, leading to the development of more advanced and reliable composites. An outline of such developments was recently listed as part of a materials forecast (Anon 1991) and hence will not be repeated herein.

COST MODELING

The relative importance of cost and performance to various sectors of the composites market is shown in Figure 7.12.

Given the specific uses of composites as "materials-by-design," it does not make sense to compare costs derived from the fabrication of a structure from composites with one from traditional materials (unreinforced polymers, metals, etc.) on the basis

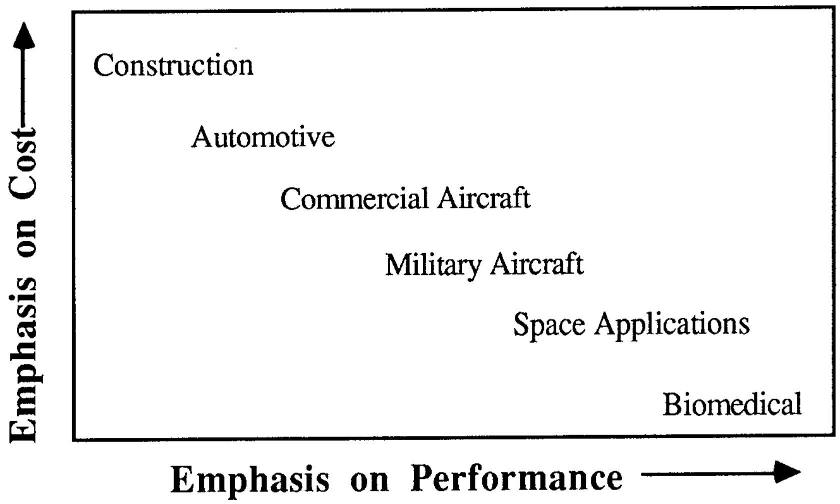


Figure 7.12. Cost-Benefit Plot (The areas may overlap and are not linear in correspondence.)

of absolute as-fabricated costs, without taking into consideration other benefits. Costs need to be compared on the basis of total value added as delivered to the customer. This brings up the concept of "life-cycle-cost", i.e., the cost/benefit ratio as perceived by the customer over the entire lifetime of the product or structure. This is especially important for composites, where the initial cost estimates may be higher than those of the incumbent metallic structures, but offer a longer and higher performance commitment to the customer.

Table 7.3 gives a comparison of cost levels between metals and composites for various stages in fabrication and use. It is evident that if a comparison were made merely on the basis of material costs, composites would not win. However, their superiority is seen when their inherent advantages are used, such as their very low assembly costs (due to the high potential for parts consolidation), and their significantly lower life-cycle costs. It is thus essential that the accounting information system (AIS) used for advanced materials systems (as for any other rapidly advancing technology) be capable of giving information that correctly interprets cost versus value. Cost and accounting information should be such that decision makers can make projections on future costs of existing and immature, as well as new or modified technologies, based on assumptions about existing technologies. This emphasizes the use of an AIS for the purposes of both profitability and strategic planning. Using traditional costing approaches a large amount of work has been conducted by Krolewski (1989), Robinson (1991), Ramkumar (1991), and others. Economic models developed by investigators at MIT and Draper labs have provided detailed quantitative evaluation of costs, and emphasize the mistakes made in

moving towards automation due to misleading indications of labor rates resulting from the mode of costing. In a recent development (Karbhari and Jones 1992), attempts are being made to use activity- based costing procedures to derive strategic cost information from a process rather than just accounting information which is of use in balancing budgets but not of use in design.

Table 7.3
Comparison of System Costs

STAGE	METALS	COMPOSITES
Raw Material Costs	Low	High
Primary Material Costs	Low	High
Parts Fabrication Costs	Low	Low
Assembly Costs	High	Can be Very Low to Negligible
Life-Cycle Costs	Base	<<< Base

DESIGN OF EXPERIMENTS, QC AND TAGUCHI METHODS

Now, more than ever before, processing costs and problems of repeatability can stall new composite programs right at the profit line. Marginal improvements in the control of composites manufacturing processes, although useful in the short term, will not provide the needed levels of quality, reliability, or economy of production. Figure 7.13 depicts the shift in approaches used to ensure product quality as a function of time. Taguchi methods belong to the class of approaches that attempt to ensure quality through design, in this case through the identification and control of critical variables (or noises) that cause deviations to occur in the process/product quality.

Taguchi methods, developed by Dr. Genichi Taguchi, refer to techniques of quality engineering that embody both statistical process control (SPC) and new quality related management techniques. Most of the attention and discussion on Taguchi methods has been focused on the statistical aspects of the procedure; it is the conceptual framework of a methodology for quality improvement and process robustness that needs to be emphasized. The entire concept can be described in two basic ideas:

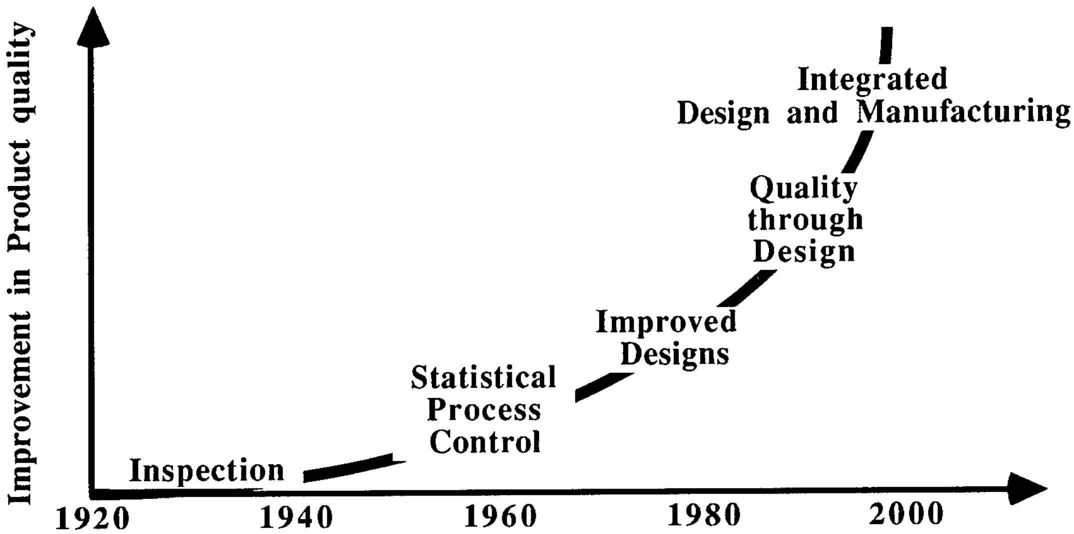


Figure 7.13. The Evolution of Quality Control

1. Quality should be measured by the deviation from a specified target value, rather than by conformance to preset tolerance limits
2. Quality cannot be ensured through inspection and rework, but must be built in through the appropriate design of the process and product

The first concept underlines the basic difference between Taguchi methods and the SPC methodology. Whereas SPC methods emphasize the attainment of an attribute within a tolerance range and are used to check product/process quality, Taguchi methods emphasize the attainment of the specified target value and the elimination of variation (Fig. 7.14). In conjunction with the second concept, this assumes great significance for composites manufacturing since Taguchi methods emphasize that control factors must be optimized to make them insensitive to manufacturing transients through design, rather than by trial and error. SPC allows for faults and defects to be eliminated (if detected) after manufacture, whereas what is really needed is a methodology that prevents their occurrence. In this case, the methodology is the use of Taguchi methods. This then presents a powerful tool for composites processing within which there is an inherent variability due to raw material quality and/or noise in the process environment itself.

Through the proper design of a system, the process can be made insensitive to variations, thus avoiding the costly eventualities of rejection and/or rework. In order to determine and subsequently minimize the effect of factors that cause variation, the design cycle is divided into three phases of System Design, Parameter Design, and Tolerance Design, as depicted in Figure 7.15.

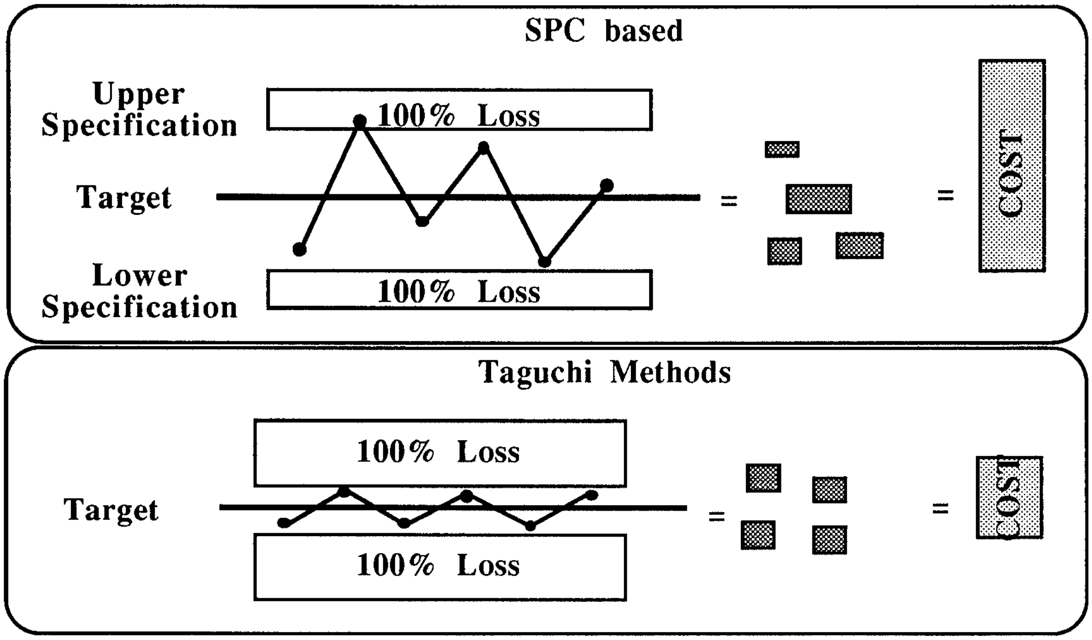


Figure 7.14. A Comparison of Methodologies

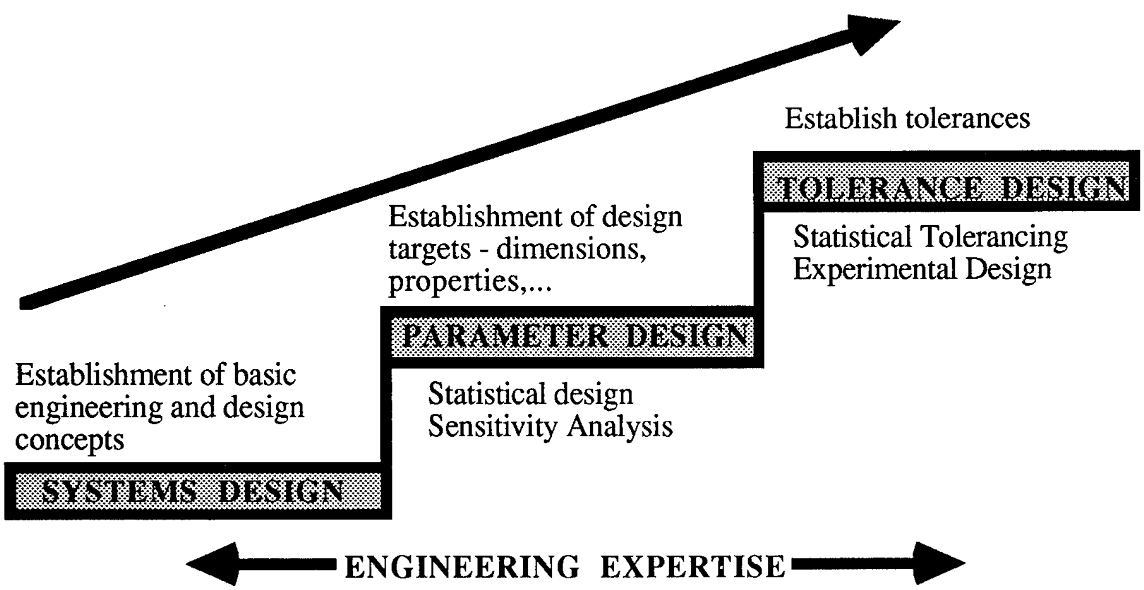


Figure 7.15. Stages in the Design Cycle

It should be mentioned that the application of Taguchi methods to plastics and composites processing has been attempted by a number of investigators (Warner and O'Connor 1989; Steele et al. 1988; Dockum et al. 1990; Karbhari et al. 1992; Slotte 1992). These include applications in the areas of injection molding and compression molding, as well as in structural reaction injection molding (SRIM) and RTM.

SOME BASIC FEATURES AND KEYS TO THE DEVELOPMENT OF PRODUCTION SYSTEMS IN JAPAN

The area of product development, although a "soft" area in terms of technology (especially in a field such as composites), is however perhaps all the more important due to the changes in paradigm necessary for a successful completion of the product realization process. Not only does the development effort need an integrated team, but it also depends heavily on team dynamics, procedures, and even intangibles such as trust and team loyalty. In addition to technological and software based advances, developments in cultural attitudes will also play a large part in the success of this area. It is interesting to look at some data from the American Quality Foundation that compares the commitment of over 500 companies in the automotive, banking, computer, and health care industries to five strategic quality elements as in Table 7.4. For ease, numbers have been rounded to the nearest five percent.

Table 7.4
Commitment to Five Strategic Elements of Quality

METRIC	U.S.	JAPAN	GERMANY	CANADA
Customer Satisfaction (primary consideration)	40	40	20	45
Competitive Benchmarking (primary importance)	30	30	5	25
Time-Based Competition (always used)	20	55	10	20
Process Simplification (always used)	10	50	10	20
Performance Evaluation (at least monthly)	55	70	55	50

It is interesting to note that the Japanese outscore all others in three key areas: time-based competition, process simplification and performance evaluation, all of which are of critical importance to the rapid and successful completion of the product realization process. Again, it has to be understood that the development of composites will only be successful if taken from an integrated perspective which includes marketing, finance, materials, manufacturing, design, and supporting elements, all of which are already present in the Japanese *keiretsu* but not in the cultures of the west. While considering aspects of the PRP it is important to note that the *keiretsu* structure (Fig. 7.16) allows the Japanese to be far more flexible than their Western counterparts because of ready made markets within close-knit *keiretsu* groups.

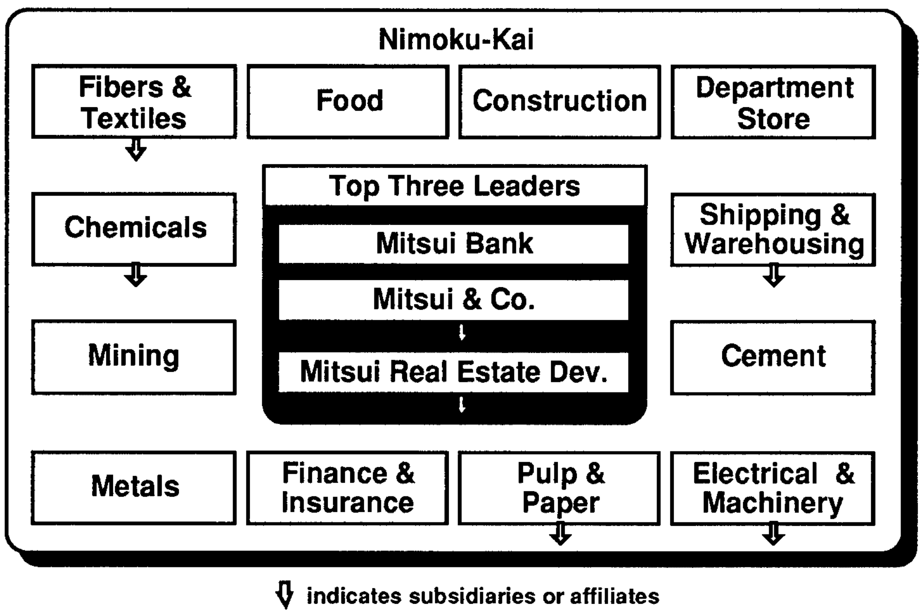


Figure 7.16. Structure of the Mitsui *Keiretsu*

In this report we will not expand on the role of the *keiretsu*, but will present, for the sake of completeness and understanding, the structure and interrelationships between companies within two of the *keiretsu* (Fig. 7.17 and 7.18), and a schematic of the overall structure and interaction between the six major *keiretsu*.

These six major *keiretsu* are linked as shown in Figure 7.19, and coexist with a number of smaller and minor *keiretsu*.

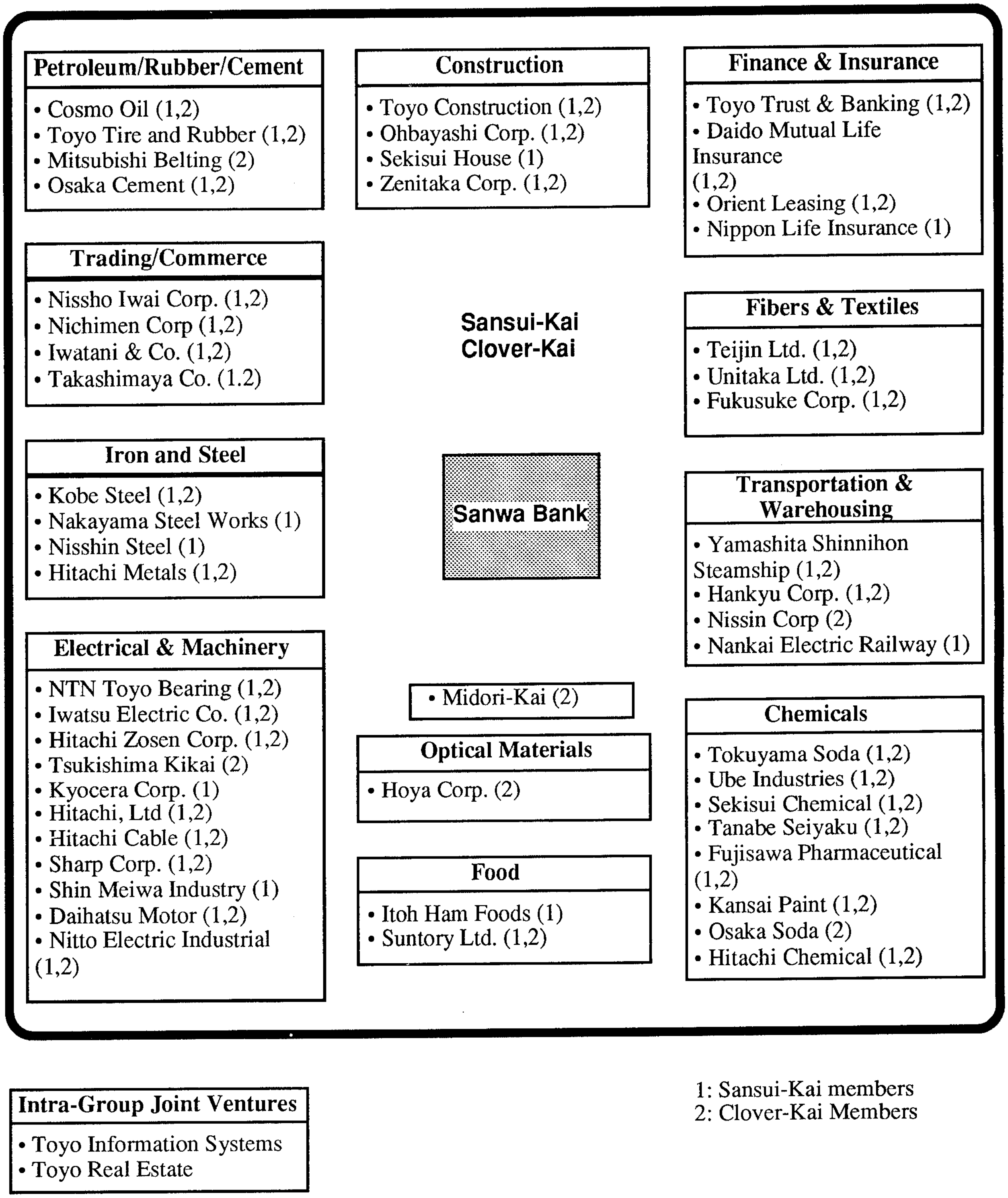


Figure 7.17. The Sanwa Group

Jugosha Shacho-Kai

- Fukoku Mutual Life Insurance
- Kanematsu-Gosho
- Shiaedo Co.
- Niigata Engineering
- Yaskawa Electric Mfg.
- Nippon Express
- Nippon Kangyo Kakamaru Securities
- Korakuen Co.
- Nissan F&M Insurance
- Denki Kagaku Kogyo
- Sankyo Corp.
- Nippon Columbia
- Seibu Department Store
- Honshu Paper

- Shimizu Corporation
- Isuzu Motors
- Kyowa Hakko
- IHI Industries
- Kobe Steel
- Asahi Chemical Industries
- Hitachi Ltd.
- Chichibu Cement
- Iseki & Co.
- Asahi Optical
- Orient Finance
- Showa Shell Corp.
- Nissho Iwai Corp.
- Lion Corp.
- Japan Metals & Chemicals
- Ebara Corp.

Sankin-Kai

Trading C. Itoh & Co.

Dai-Ichi Kangyo Bank (DKB)

Kawasaki Mutsumi-Kai

- Kawasaki Steel
- Kawasho Corp. (Subsidiary/Affiliate of Kawasaki Steel)
- Kawasaki Heavy Industry
- Kawasaki Kisen

Furukawa Sansui-Kai

- Asahi Mutual Life Insurance
- Taisei F&M Insurance
- Asahi Denka Kogyo
- Nippon Zeon
- Yokohama Rubber
- Furukawa Co.
- Nippon Light Metal
- Furukawa Electric
- Fuji Electric
- Fujitsu Ltd.
- Shibusawa Warehouse

Chemicals

- Tokuyama Soda (1,2)
- Ube Industries (1,2)
- Sekisui Chemical (1,2)
- Tanabe Seiyaku (1,2)
- Fujisawa Pharmaceutical (1,2)
- Kansai Paint (1,2)
- Osaka Soda (2)
- Hitachi Chemical (1,2)

Intra-Group Joint Ventures

- Century Leasing System
- Century Research

Meiji Group

- Meiji Seika
- Meiji Milk Products
- Meiji Machine

Trading Firm

Figure 7.18. The DKB Group

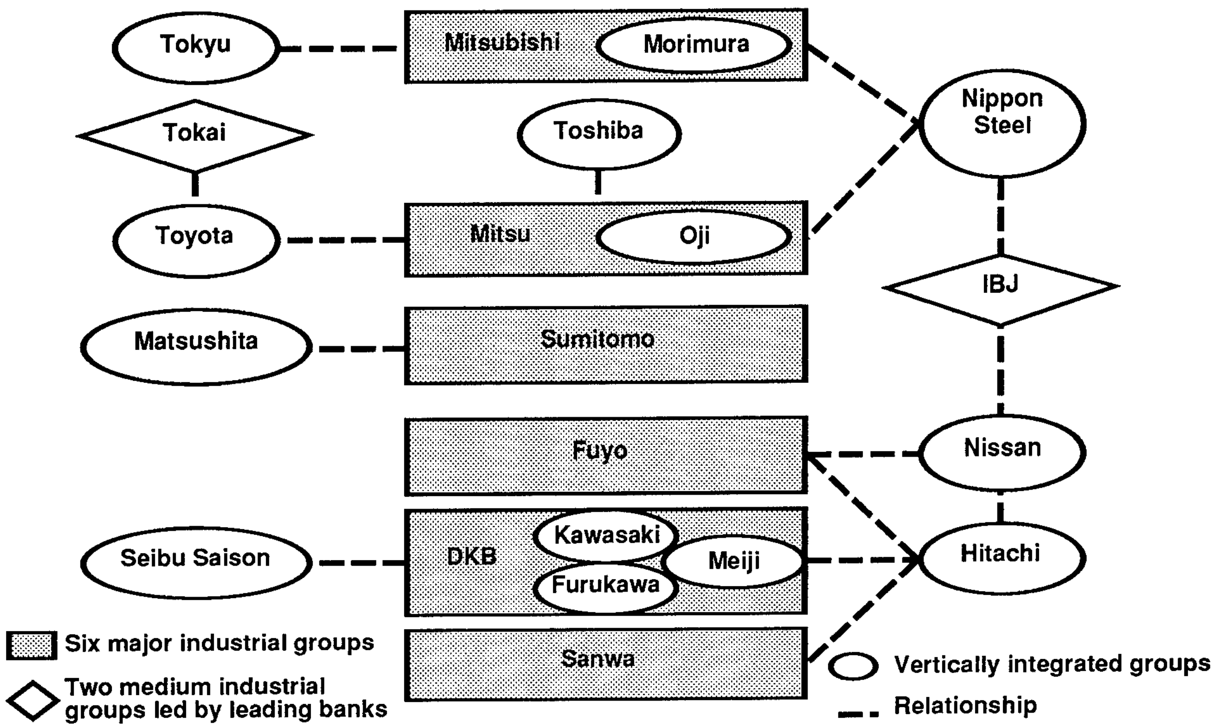


Figure 7.19. Interactions Between Major *Keiretsu* and Other Groups

It is emphasized that this structure allows companies to speed up the PRP because of the presence of vertically and horizontally integrated teams, very often presenting both the developer, marketing arm, and customer as different companies within the same *keiretsu*.

In overall terms the approach to product development followed by the Japanese can be described by the following:

1. **The Development of a More Creative Labor Force.** Almost all companies have extensive education programs led by senior managers who make a concerted attempt to pass on their knowledge to the rest of the team. In the case of companies such as Yamaha, senior managers are instrumental in putting together textbooks listing the sum total of their knowledge in the form of design rules and heuristics for the other members of the team. In the case of companies such as JAMCO, entire production lines are set up with the human element in mind. If errors occur, the individuals are educated in the

appropriate technology, and simultaneously the existing production environment is investigated to determine if changes are necessary to make the best use of human capabilities. There is virtually no finger-pointing and the effort is spent on correcting the error at its source. The focus in all cases is the creation of a more creative work force, keeping in mind that people cannot be replaced by machines, even in the ultimate projection of computer-integrated manufacturing; primary human work cannot be automated.

2. **The Development of Global Corporate Strategy**. Management strategy is aimed at long-term gains in a global market and corporate strategy is laid with those goals in mind. Investment in research consortia, joint ventures, and partnerships is encouraged and is expected to be substantial and reciprocal in nature. As part of its global strategy, Shimizu, primarily a construction and civil engineering firm, has included areas such as information systems, desert urbanization, computer hardware and software integration, and outer space development among its market aims. Established in 1804 as a construction company, Shimizu has joint ventures or subsidiaries in Sweden, Germany, France, Hong Kong, Netherlands, Malaysia, Australia, Thailand, Canada, the U.S., China, and the U.K. in areas of construction, properties, investment, and finance. It is interesting to note that unlike the major aerospace primes in the U.S., whose main business is in one market segment, the "Heavy Industries" companies in Japan (MHI, KHI, IHI) are more diversified, as shown by the typical breakdown of sales by percentage (Fig. 7.20).

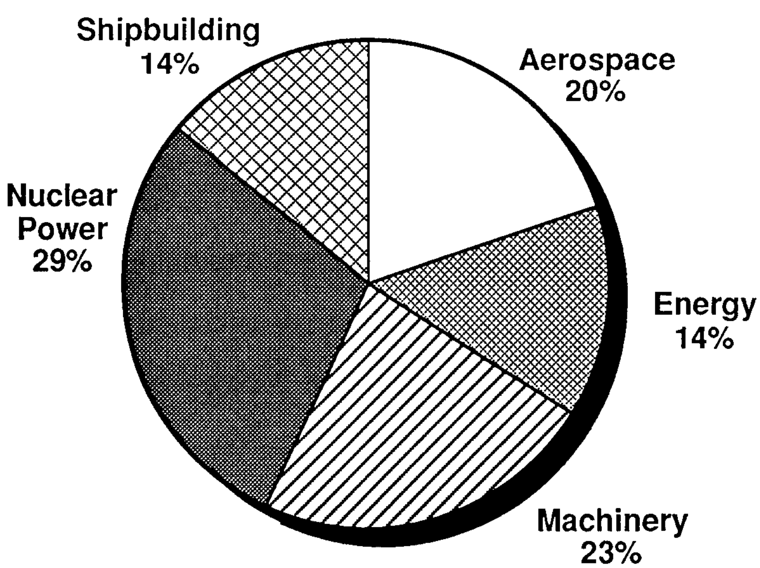


Figure 7.20. Percentage of Sales for a Typical Japanese "Heavy Industries" Company (after M. Ashizawa)

3. **The Integration of Technology with Information Systems**

4. **The Combination of Large Leaps and Small Steps**. Japanese companies are increasingly accepting that a singular breakthrough strategy is no longer adequate because it focuses R&D efforts into narrow arenas, ignoring possibilities for combining elements from different areas. Technology fusion, a term coined by Fumio Kodama, is becoming more and more apparent as companies try to combine advances in different areas in order to stay competitive in a global economy. Leading high-tech companies in Japan are following a major trend of diversification (a few examples are given in the section on case studies). The textile industry is one such example in which large R&D budgets are expended on subjects that do not relate directly to the textile or garment industry (e.g., composites in construction and building materials, as is being done by Asahi-Kasei). Toray Industries is another example where technology fusion is practiced. This company monitored the advances made by other institutions such as Union Carbide, the Royal Aircraft Establishment in the U.K., and the Japanese government research labs, and articulated the need for new products and hence material forms in both the sporting goods and aerospace areas. Extensive joint research projects are conducted in collaboration with customers, and innovative products are brought to market quickly through the adaptation of advances made in other areas to the production of carbon fiber and other products using carbon fiber.

Most companies aggressively pursue the search for new markets, even going as far as creating a demand for a product through aggressive demonstration projects, such as is currently being done in the infrastructure rehabilitation area. Very often the *keiretsu* structure is used to find the initial customers and create the acceptance. There is an increasing search for new partners with the emphasis being on increased sharing of development costs and risks, as well as the need for new ideas through technology fusion. Of late there has been a significant increase in alliances and long term agreements between Japanese and International firms; the trend is seen in the composites area as well with Tonen, Toray, JAMCO, and KHI being examples. The increase in collaborative R&D, as well as in joint ventures, is also an attempt to lock in their customer base. For further details the interested reader is referred to the excellent collection of papers in a book published by the National Research Council (1992).

MITI AND ITS PERCEIVED ROLE

The Ministry of International Trade and Industry (MITI) was established in May 1949 and has focused on the development of the Japanese economy and industry. It is in charge of the administration of affairs related to foreign trade, industries, information, advanced technologies, environmental issues, energy, and other such

issues. With an annual budget of over ¥2,699 billion, MITI's budget accounts for about 1.1% of the Japanese government's total general budget. Of special interest to this study is the role played by the Agency for Industrial Science and Technology (AIST), which is charged with planning comprehensive measures concerning scientific technology in the manufacturing and mining industries, conducting research and development, encouraging technological development in the private sector, and instituting and promoting the wider use of industrial standards. It is this agency that is responsible for the development of basic technology and for planning for the future.

In a recent development, MITI and AIST plan to combine all offices responsible for managing research projects open to international participation into a single administrative entity that would be organized into eight divisions:

1. New Materials
2. Bio-Technology
3. Electronics, Information Processing, and Communication
4. Machine Technology
5. Aerospace
6. Medical and Welfare
7. Human, Life, and Society
8. Natural Resources

As part of this process 55 research themes have been identified, which include the following related to composites under the specific groups:

1. New Materials:
   - o polymeric materials with highly precise structure
   - o autonomic materials
   - o organomagnetic materials
   - o cluster materials
   - o environmentally-friendly materials
   - o computer chemistry (modeling)
   - o hyper-reliable inorganic fused materials
   - o amostal (amorphous crystal) materials
   - o high performance carbon materials

2. Biotechnology
   - o self-organized materials (including biopolymers)

3. Machine Technology
   - o advanced tribology (including composite wear surfaces)

4. Aerospace
   - o supersonic transport planes/hypersonic transport planes
   - o high performance vertical takeoff and landing airplanes

Fiscal year 1993 research projects have been selected and categorized from among these themes.

In recent years it has been suggested in the West that a significant amount of credit for the amazing progress made by Japanese firms is due to MITI-supported initiatives. MITI does plan and initiate large, long-term projects that integrate leading companies (as was done with the major "heavy industries" companies and NAL in the area of composites). Most projects have a focused vision with technology development and dissemination as key and critical aspects. It should be noted that there is very little involvement of small companies through set-asides in these projects, and recently there has been a major push to increase the participation of international companies and institutes. This is seen as a means to create and capture new markets through the complete participation of the end customer in the development stages itself (such as through the participation of companies such as Boeing and DuPont). Although it is often presumed that the amount of funding generated by MITI for such projects is high, companies visited by the team were quick to point out that it basically served as a catalyst for IR&D funding and for the creation of teams for pre-competitive technology development. The companies often put in much more money than MITI's initial contribution, which essentially serves as a start up for long-term projects focused on critical technologies. Irrespective of this, the important role played by MITI in the emergence of Japanese companies as world leaders should not be understated.

It may be of interest here to report on the results of a MITI organized panel that was charged with listing areas other than their own from which they expected major new advances. Table 7.5 summarizes the results for seven fields in the short term (0-5 years) and long term (5-10 years).

According to the scores and percentages, the electronics area was thought to hold the most promise in the short term, followed by materials. Although the government-supported projects in the areas of aerospace and energy had produced a significant number of breakthroughs in new materials, it was held that the development of materials was now expected to be in direct response to specific technical needs, rather than as a result of a larger project. Over the long term, however, the expectations for materials were significantly higher than for the other fields, reflecting the widely held belief in Japan that new breakthroughs in areas would be prompted by advances in the materials area. This may be one reason why there is still a considerably increasing investment in composites R&D, even after the global defense markets have shrunk. However, it should be noted that Japanese scientists do not expect these composites to be the same as those developed earlier. The current

emphasis is on "fourth-generation" materials, i.e. those which are designed by controlling the behavior of atoms and electrons, and which provide carefully tailored functional gradients.

Table 7.5
Expectations of Advances

AREA	POSSIBLE NO. OF RESPONSES	SHORT TERM (0-5 YEARS)		LONG TERM (5-10 YEARS)	
	A	B	B/A (%)	C	C/A (%)
New Materials	128	85	66	94	73
Biotechnology	130	14	11	62	48
Electronics	130	94	72	78	60
Information	119	72	61	68	57
Energy	126	27	21	45	36
Aerospace	131	23	16	38	29
Construction	130	14	11	16	12

Source: Japan Society for the Promotion of Machinery Industry 1990

CASE STUDIES

In this section we briefly touch on aspects of product development through examples gleaned from the team's visits. Wherever possible, the structure of the company/institution under consideration is highlighted and emphasis paid on aspects that are different about the approach under consideration. It is not possible to present a detailed picture of new product development methods and approaches as used by the Japanese within the confines of a few pages, and it is hoped that the few examples will give the reader a glimpse of the varied activities undertaken to ensure success of the product realization process.

Tonen Corporation

Most companies develop products within certain set bounds in terms of application areas. We briefly consider in the context of this chapter the background and development of an advanced material form -- Tow Sheet -- by Tonen Corporation, as an example of a company developing a market beyond its specific area of past activity. This example is used here for a number of reasons:

- o This is a company which has a significantly different structure from the traditional.
- o The product form was developed as a means of competing and improving on a competitor's idea.
- o The company is not a major player in the carbon fiber market, but is using this as a means of increasing overall sales and market share.

It is perhaps of interest to note that Tonen, unlike other Japanese companies, is actually a mix between a traditional Japanese held company and a multinational joint venture between Esso Eastern Incorporated, Tonen Corporation, and Mobil Petroleum Co., Inc. Figure 7.21 gives a schematic of the outline of the company, and Tables 7.6 and 7.7 give brief details of the major shareholders as the major sources of financing, as reported in the 1991 annual report.

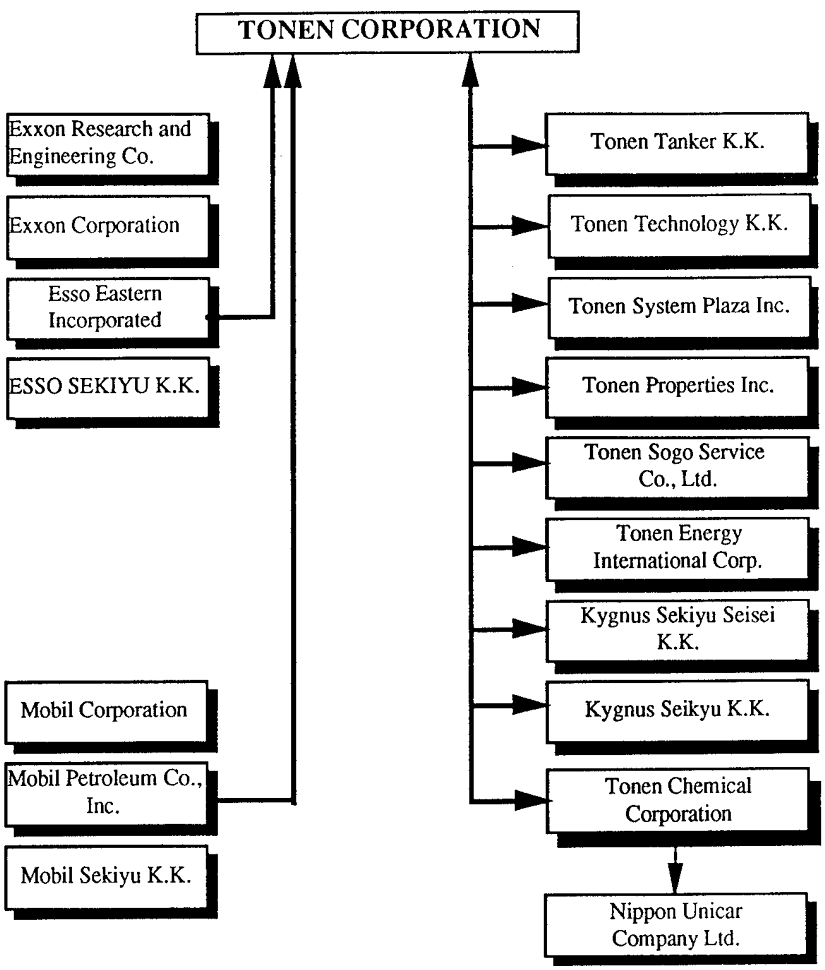


Figure 7.21. Organizational Structure of Tonen Corporation

Table 7.6
Major Shareholders in Tonen Corporation

SHAREHOLDERS	SHARES HELD		SHAREHOLDERS' SHARES HELD BY TONEN CORP.	
	(1000s)	%	(1000s)	%
Esso Eastern Inc.	161,636	25	-	-
Mobil Petroleum Co., Inc.	161,636	25	-	-
Fuji Bank, Ltd.	26,353	4.08	9,436	0.33
Industrial Bank of Japan, Ltd.	26,353	4.08	8,781	0.37
Yasuda Fire and Marine Insurance Co., Ltd.	18,205	2.82	200	0.02
Tokio Marine and Fire Insurance Co., Ltd.	18,205	2.82	-	-
Yasuda Trust and Banking Co., Ltd.	17,673	2.73	1,400	0.13
Dai-ichi Kangyo Bank, Ltd.	11,643	1.80	1,308	0.04
Nippon Life Insurance Co.	8,680	1.34	-	-
Chiyoda Fire and Marine Insurance Co., Ltd.	8,529	1.32	-	-

Table 7.7
Major Sources of Financing

LENDERS	BALANCE OF OUTSTANDING LOAN	SHARES HELD OF TONEN CORP.	
	¥ (million)	(1000s)	%
Japan National Oil Corp.	30,053	-	-
Fuji Bank, Ltd.	11,811	26,353	4.08
Dai-ichi Kangyo Bank, Ltd.	8,423	11,643	1.80
Industrial Bank of Japan, Ltd.	6,503	26,353	4.08
Japan Development Bank	6,374	-	-
Sanwa Bank, Ltd.	5,050	1,500	0.23
Mitsubishi Bank, Ltd.	3,992	7,727	1.20

It is interesting to note that the major business of the company is in the import, production, and sale of petroleum and petroleum products, including gasoline, naptha, kerosene, gas oil, heavy fuel oil, lubricants, LPG, paraffin, asphalt, sulphur, natural gas, and carbon fiber. The joint venture was facilitated to assure the ready import of crude oil from its multinational partners, in itself an example of a strategy to assure product development. In the context of this chapter, however, we will focus on the development of a new business area for the company -- that of advanced materials for infrastructure rehabilitation.

Tonen had a preexisting materials capability in production of liquid crystalline petroleum pitch based carbon fiber. Based on work conducted by its rival Mitsubishi Kasei and Ohbayashi Corporation in the area of seismic retrofit of structures through the use of carbon prepreg, it was determined that the company might be able to diversify into a new market if it could develop a form of prepreg that would allow ease of drapability and use in the field. Based on the identification of the drawbacks of the existing product and process, Tonen engineers and scientists developed a modified material form known as "Tow Sheet."

In the initial form, it consists of 10-micron diameter filaments of carbon with a tensile strength of 3300 MPa (470 ksi), and a tensile modulus of 700 GPa (100 Msi) applied on the top of a thin layer of scrim (Fig. 7.22). The "FORCA Tow Sheet" is thin and applied like wallpaper to structures, and has been shown to be extremely amenable to application to a wide variety of structures without having to rely on expensive equipment. Tow Sheet has since been improved through a modification in form, and is now available in glass, aramid and a variety of carbon grades. This case emphasizes the identification of a pre-existing materials capability and that of the needs related to a new market, which lead to the development of a new material form -- a case of market development needs leading to the development of a new product.

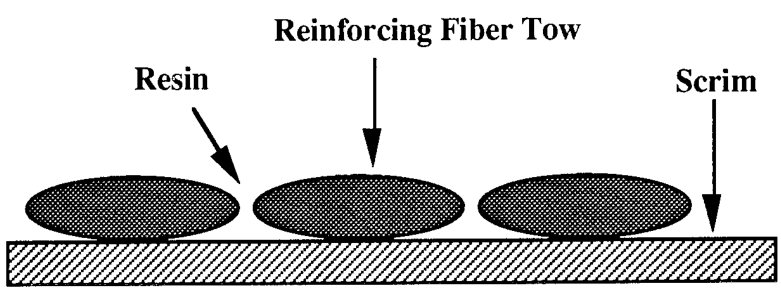


Figure 7.22. Schematic of Tow Sheet

Mizuno Corporation

In another case study we briefly consider the overall development strategy used by Mizuno Corporation. Mizuno is a world leader in the area of sports equipment, sportswear, and other items related to sports, including, recently, the development of sports facilities. The company was started in 1906 and incorporated in 1923. Unlike other powerhouses in Japan, Mizuno is an independent company, not directly linked to any *keiretsu* (in itself a reason to comment on its product and market development strategies). It currently has 4,080 employees and a paid up capital of over ¥26 billion. Mizuno has 17 production facilities around the world with 12 factories in Japan and five abroad, including one in Norcross, Georgia which primarily services the golf products area. The company uses an integrated information system to aid in both production and strategic planning, and a schematic of the setup is shown in Figure 7.23.

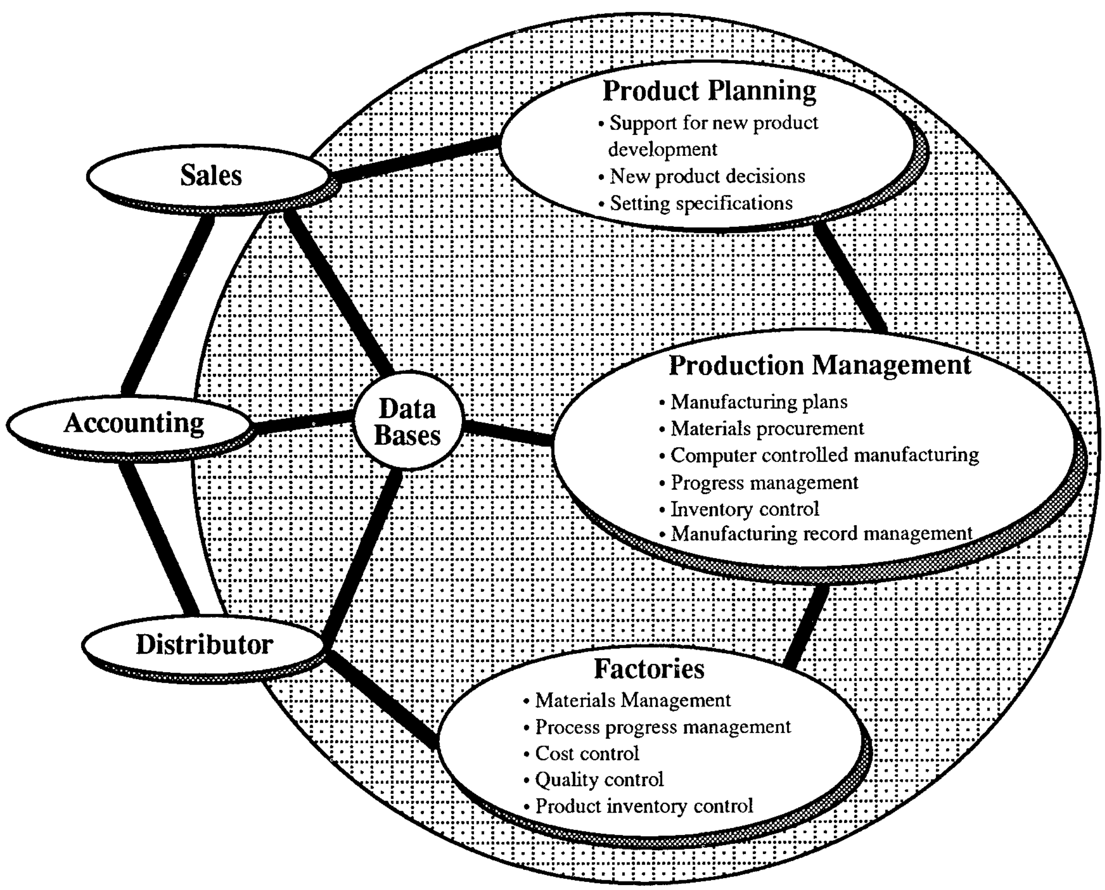


Figure 7.23. Total Information Control as Espoused by Mizuno -- From Management to Cost, Process and Stock Control

In order to stay competitive in the sports equipment arena, Mizuno picks new products by searching for specific applications where high performance composites would give increased benefits and enable product forms not possible with traditional materials. One case in point is the development of composite large head tennis rackets not possible with wood or metal due to stiffness and weight constraints. Mizuno is also a major player in the carbon fiber composite golf club market. In recent years they have collaborated with Pininfarina (Italy) on full scale aerodynamic studies to improve head speed, such as in the development of the optimized ZP-1 club. As part of its development strategy, Mizuno uses automated integrated production lines with state-of-the-art computer integrated manufacturing facilities to meet the needs for small-lot production. This allows them to develop new products cost-competitively using a variety of different processing methods as well as in a number of simultaneous variations. Product development is followed by market insertion through the use of high profile "advisory staff" that includes athletes such as Sandy Lyle (golf), Ivan Lendl and Mary Joe Fernandez (tennis), and Franck Piccard (skiing). Golf products (34.3% of sales in 1992, and a major user of composites) are promoted through the use of travelling golf schools.

Mitsui Mining Company Ltd

Although a number of carbon fiber suppliers have been very active in the development of short fiber forms for use as reinforcement in concrete, there still exist the two basic problems associated with its widespread use: (1) cost, and (2) development of adhesion between the fiber and the slurry. The promise of a large potential market served as the impetus for Mitsui Mining Company Ltd. to develop a new "fuzzy" fiber form that is claimed to be both cheaper and to have a strong affinity for concrete slurry. The fiber has a diameter of 16-20 microns, a density of 0.06 lbs/in^3 (1.6 gms/cm^3), and a tensile strength and modulus of 113-128 ksi and 4.7-5.4 Msi, respectively. The cost reduction and hydrophilic surface are obtained simultaneously through the use of a lower cost precursor, low cost solvent (water), and a less intensive pyrolysis. The actual secret, however, would seem to be in the realization that the civil engineering market had different requirements from the traditional aerospace/automotive markets for reinforcement in the form of short fibers. This was followed by the quick development of a process suited to the requirements (many of which would cause the fiber to probably not qualify for use in aerospace applications). The development of what has been largely touted as a "new material" is actually a lower quality form of a pre-existing form, but one modified for the specific needs of an application.

Sumitomo Precision Products Co. Ltd.

This was a rare case of a joint project between a university research group (Kyoto Institute of Technology) and a company, aimed at the development of a new product. Through the previous development of a variety of products, Sumitomo had identified the joining of composite tubes and profiles as a major problem. Existing

connections were based on steel design, highly unsuitable for use with advanced composites. Driven by the need for innovative solutions to stop failure of the more effective composite structures at joints, the team used an integrated materials, configuration, and processing approach to develop braided connections. These were developed through extensive simulation and experimentation and are now available as hybrid (carbon-glass) structures, allowing the connection of multiple members. Again, this case study emphasizes the identification of a specific niche need, followed by the rapid development (through extensive experimentation at a leading university laboratory) of an innovative solution, which was used to improve the company's own products.

Yamaha Motor Co.

Almost all new product development by established companies is conducted in the broad area of technology (or market sector), in which the company has a pre-existing stake. In this section we briefly discuss a case where this did not hold true. Yamaha Motor Co., Ltd. is a comprehensive manufacturer of products ranging from sports and leisure goods to industrial equipment. Its mainstays, despite considerable diversification in recent years, remain motorcycles (45.8% of sales), marine products (20%), and power products (multipurpose engines, generators, outboard motors -- 16.7%). However, the company is in constant pursuit of new markets and business opportunities leading to the development of "new and original quality products that are at least one step ahead of the times." Product insertion in the traditional sense is done through publicity generated by participation and victory in high profile sporting events, such as Grand Prix automobile racing, motorcycle championships, Americas Cup (sailing), and events such as the solar powered and human powered boat races, in much the same way U.S. firms do. In one case however, Mr. Horiuchi, Director and Senior General Manager of the Marine Division, and his team identified the need for a method of applying pesticides to small fields in a rapid manner, without human intervention (for reasons of health). Once the need for a new product was identified, the team developed a concept through combined IR&D and government funding, in an area in which Yamaha as a whole had very little experience, and the division in question had none. It was determined that a small remote controlled helicopter would be the most efficient solution, and one was developed and transitioned into a production line item (albeit small) in less than six months. The R-50 helicopter has a fuselage of 2655 mm in length, and a main rotor of 3070 mm in diameter powered by a 98 cc. engine. In order to keep weight to a minimum and allow a sufficient payload capacity for pesticides, the blades and body enclosure were fabricated out of composites using procedures borrowed from their boat-building yards (total weight of helicopter = 67 kg.). The helicopter is now commercially marketed and is an example of new product development for a niche market. Two aspects stand out in this case study:

- the identification of a need and rapid development of a product for a niche market

- o the participation and championing of the product concept by the Senior General Manager, who worked as an integral part of the product development team, rather than as an administrator.

Toray Industries

In order to secure a long-term market for its graphite fiber business, Toray worked through the hiring of Boeing veteran Malcolm Katsumoto to secure its business on the Boeing 777. This was seen as a spectacular success in prepreg, as Boeing opted for a toughened Toray system for the tail and floor beam (both primary structures) on the 777 aircraft. In order to keep the market and its edge over other rivals, Toray put up a 4.5 million square foot prepreg plant in Seattle. The prepreg contains Toray's 3900-2 epoxy with uniformly dispersed thermoplastic microparticles and Toray's T800H PAN-based carbon fiber. This case highlights two points:

- o the hiring of a person to ensure connections and help in cementing a relationship
- o the development of a facility that now makes Toray a volume prepregger, which has decreased the use of Toray's fiber as a feedstock for other prepreggers, in relation to the increased demand for prepreg

New products are driven to become realities through concentrated efforts using existing structures, but while also striving to develop new materials, equipment, designs, and skills to optimize the entire development. It is emphasized that most Japanese teams consider that integration of different facets leads to larger gains at the systems level and strive towards that goal, rather than towards narrow, field- and level-specific goals. This may very well be an attribute of the different management structures prevalent in the companies scrutinized.

AN EXAMPLE OF MANAGEMENT STRUCTURE

In studying product development methods and the inherent differences between methodologies followed by the U.S. and Japan, it is useful to keep in mind the differences in management structure, even outside the idea of a *keiretsu*. Rather than delving deeply into the intricacies of the management of Japanese companies and the structure of the *keiretsu*, both of which are well researched and documented subjects (although probably not well understood even today in the West), we provide an example of the structure of a large Japanese company, emphasizing the parts relevant to composites.

Nippon Steel Corporation is the largest producer of crude steel in the world, with 1991 production figures in excess of 28.6 million tons. The company's "rich endowment of capabilities and experience is now beginning to flow into (diverse)

fields beyond steelmaking," one of which is the area of carbon fiber and advanced composites. Its management philosophy is best summed up by the lines they used to describe their company: "Like a great river, flowing steadily but changing constantly, the history and work of Nippon Steel are a matter of both tradition and transition." It is a "tradition" of over a hundred years of steel-making that in their words "encompasses new technologies to make steel ... a tradition that does not - and will not - change." It is a "transition" in that as the company developed new areas to solidify its role in the steel market, it built up technologies and know-how in the areas of civil engineering and building construction, regional development, information systems and analysis, transportation systems, chemistry, ecology, and environmental protection, all of which lead to diversification into new business lines. These include new and profitable businesses in engineering, urban development and building construction, electronics/information systems, new materials, chemicals, and life-related service businesses. These today account for 25% of Nippon Steel's total sales and are projected to expand to over 40% in the next few years. The emphasis is not on decreasing the role of its steel making industry but on expanding its markets. In the case of carbon fiber and composites, the basic premise is that as steel is replaced by advanced materials (ceramics, carbon, and advanced composites), Nippon Steel will be in a strong position to sell those materials, thus positioning itself for diversification and replacement in order to hold and expand markets and market share in a global economy. The competition between its different products is not seen as a disadvantage, but a move towards increased market share and a hold on both traditional and emerging market segments.

The Technical Development Bureau (TDB) coordinates and directs R&D activities in six different laboratories: (1) Steel Research Laboratories; (2) Process Technology Research Laboratories; (3) Advanced Materials and Technology Research Laboratories; (4) Electronics Research Laboratories; (5) Plant Engineering and Technology Center; and (6) R&D Laboratories at the steelworks.

The company's entire research and development budget is allocated to the TDB, which then allocates these resources to the different segments. However, only 40% of the resources are directly controlled by the TDB, with the other 60% being virtually directed at the behest of individual research groups. The groups primarily function as independent units within an overall company strategy. The TDB, however, serves to promote integrated research, consistently match R&D actions with management and business needs, and focus efforts towards new ideas.

The primary emphasis is on linkage and integration from actions in the laboratories, so as to enable early and effective realization of technology. Rather than focus on activities such as R&D, the groups are encouraged to think in terms of "research & engineering," linking traditional R&D roles with those of engineering, to create a technology fusion through innovation. Again, as was seen in a number of other Japanese companies, there exists a critical blend of product development with

process development, resulting in practical and immediate applications, rather than just innovative ideas that do not see the production floor. Basic research is thus focused towards engineering applications rather than on isolated ideas.

It is interesting that within the overall structure, research group leaders are expected to interact with customers and develop market areas for the company. They are encouraged to make generic (rather than product specific) presentations on materials and or application techniques to customers, allowing ideas to surface as "joint" ideas. Developmental work is done quickly, often at company cost, to prove viability and develop a sense of trust. The team is then exhorted to have constant interaction with the customer and suppliers, building a sense of trust and commitment and inculcating a feeling of joint ownership and membership in the team, an idea that we are now pushing under the TQM revolution. It is somewhat surprising, however, to note that these ideas are so firmly ingrained that when questioned, team members do not claim to be using any special TQM techniques, but they do so almost as a matter of course.

RESEARCH AND DEVELOPMENT ON 3-D WOVEN COMPOSITES

The establishment of the Three-D Composite Research Corporation is an example of major Japanese companies forming a precompetitive joint venture to initiate research and development in an area that is assumed to have significant future market potential. The consortium was established in March 1988 with the aim of developing prefabrication and preforming techniques for 3-D structures in a cost-effective and efficient manner. The companies involved in this venture are Mitsubishi Electric Corporation, Nippon Steel Corporation, Toyoda Automatic Loom Works, Ltd., Mitsubishi Rayon Co., Ltd., and Arisawa Manufacturing Co., Ltd.

The formation of such a venture is all the more remarkable because it is in an area that is highly competitive and all the companies involved had already committed significant resources to in-house development before its formation. The results of the venture have been outstanding, ranging from the development of new equipment and material forms, to the actual demonstration of complex forms, and the determination of mechanical and physical data.

OVERALL REMARKS AND CONCLUSIONS

Fumio Kodama has identified five emerging "techno-paradigm" shifts that are apparent in Japanese companies (Kodama 1991); these were seen in the polymer composites area by the JTEC team as well:

1. manufacturing companies -- from producing to thinking organizations
2. business dynamics -- from single to multiple-technology base (diversification)
3. R&D activities -- from visible to invisible enemies (competition from other industries rather than from industries within the same industrial sector)
4. technology development -- from a linear to a demand articulation process (a focus on how to put existing technology to the best possible use)
5. technology diffusion -- from technical to institutional innovation

It would appear that these shifts have been accepted by the leading Japanese companies who are now working on a very different level from that seen a few years ago.

The JTEC team drew the following overall conclusions concerning product and process development in Japan:

- o Japanese product and process development use concurrent engineering by definition. Japanese teams have developed the human factors issues far beyond those in the West.
- o Longer development lead times for projects are allowed in Japan than in the U.S., and investigators are given greater latitude and confidence for long-term gains.
- o Products are often highlighted through demonstration projects.
- o Materials development is applications driven.
- o The product/process realization team is committed at an individual level to the project, and works together with full management backing.

The JTEC group felt that although the state of technology was about the same in both countries, Japan would seem to hold a lead in bringing products rapidly to market. Some reasons for this have been given in this chapter, while others relate directly to the socio-political and economic conditions prevalent today. Although much has been made of the methods used by the Japanese and the critical need for their acceptance by the U.S., it is this author's opinion that blanket copying of approaches will not solve problems, nor will it narrow the perceived gap in competitiveness. The methods used by the Japanese are largely rooted in their cultural background and psyche, and it is improbable that the approaches would find successful applicability in regions where the culture and people are in many cases asymmetrically aligned. However, we would do well to learn from them in aspects related to precompetitive collaboration, worker education, and in what may loosely be termed "individual responsibility."

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APPENDICES

APPENDIX A. PROFESSIONAL EXPERIENCE OF PANEL MEMBERS

Dick J. Wilkins

Dr. Wilkins is Professor of Mechanical Engineering at the University of Delaware. His research involves design of composite structures and the application of engineering principles to manufacturing process development. He is a Fellow of the American Society for Composites, and served as its President from 1990 to 1992.

From 1991 to 1993, he served as Executive Director of the Institute for Applied Composites Technology, a new organization dedicated to expediting applications of composites, and was also President of the Delaware Technology Park.

He joined the University of Delaware in 1986 as Director of the Center for Composite Materials (CCM) and Professor of Mechanical Engineering. He is now a member of CCM's Board of Directors.

He previously worked for 17 years with the Fort Worth Division of General Dynamics Corporation, where he was responsible for numerous structures technology development activities in composites. He was educated in Aerospace Engineering at the University of Oklahoma, where he received his B.S., Master of Engineering, and Ph.D.

Motoaki Ashizawa

Motoaki Ashizawa is Chief Consultant of Ashizawa and Associates Composites Engineering (AACE) of Woodinville, WA. Previously, he served as manager of the Composite Structural Technology Group at McDonnell Douglas Corporation, where he was responsible for more than 15 different projects including the HSCT (High Speed Civil Transport) project. One of his assignments for McDonnell Douglas was as program manager of MD-11 Composite Rudders Program, which was a cooperative program with Alenia of Italy.

Mr. Ashizawa has 26 years of experience in design, analysis, and development of commercial as well as military aircraft structures, particularly in the area of advanced composite structures. In the past he has managed, directed, and worked on numerous research and developmental programs sponsored by NASA, the Air Force, the Navy, and McDonnell Douglas. Many of the research projects resulted in

advanced techniques and designs that are utilized in today's composite structures used in commercial and military aircraft.

He received his B.S. (Aerospace Engineering) from California Polytechnic University in 1967 and his M.Sc. (Engineering Mechanics) from California State University in 1970. Mr. Ashizawa has earned worldwide recognition as an expert in the area of composites. He has received several awards and honors as well as having numerous papers and technical articles published.

Jon B. DeVault

Mr. DeVault is currently a Senior Scientist for the Defense Sciences Office at the Advanced Research Projects Agency (ARPA), where is he involved in organizing the Defense Conversion Composites Initiative. He came to ARPA in 1993 from the University of Delaware, where he worked on a DARPA grant to support the university's strategic planning in the area of advanced composites. Prior to that, Mr. DeVault led a distinguished career with Hercules, retiring in 1992 from the position of Managing Director of Ventures and Business Development for Hercules Materials Company. He joined Hercules in 1962 as a physicist at its Alleghany Ballistics Laboratory (ABL). Between 1962 and 1969, he worked on propulsion systems for the Polaris and Poseidon programs at ABL, and later at the Hercules Bacchus Works in Salt Lake City. In 1969, Mr. DeVault helped establish Hercules' graphite materials business. In 1982, Hercules created a separate business unit to pursue composite structures under Mr. DeVault's leadership as president and general manager for composite structures, Hercules Aerospace Division. In 1989, he was appointed president of the Composite Products Group, Hercules Aerospace Company.

Mr. DeVault received his B.S. and M.S. degrees in Physics and Mathematics from Baylor University in 1960 and 1962, respectively. He is a member of Alpha Chi and Sigma Pi Sigma, and has been an active member of SAMPE, SACMA, and ADPA.

Dee R. Gill

Dee Gill is currently Director of Manufacturing in the New Aircraft Division of McDonnell Douglas Corporation. At McDonnell Douglas he has been involved in work on the A-12, the ATF, and the AX, with the responsibility of developing systems to turn designs into product. He is also involved in the study and implementation of systems like manufacturing requirements planning and other processes that improve factory flexibility and throughput. Prior to coming to McDonnell Douglas in 1989, Mr. Gill worked for Hercules, Inc. for more than 25 years, where he was involved in all aspects of fabricating composite structures from the production of Boeing 757 and

767 parts, to developing filament winding into fiber placement. In the operation of the composite structures facility he was involved in all aspects from design to production including the transition from prototype to production. Mr. Gill holds several patents, such as the segmented expandable mandrel, fiber placement machine, and the machine for producing composite drive shafts.

Mr. Gill received a BSME from the University of Idaho in 1963 and was a graduate of the Naval Nuclear Power School in 1965.

Vistasp M. Karbhari

Dr. Karbhari is currently a Scientist at the Center for Composite Materials and Research Assistant Professor of Civil Engineering at the University of Delaware, where he leads efforts in manufacturing science for composites and the application of composites to civil infrastructure. In addition to his thrust in infrastructure renewal, Dr. Karbhari's current research areas include composites manufacturing and mechanics; interphasial studies; fracture, damage, and crush; design methodologies; and recycling. He received his Ph.D. from the University of Delaware for his research on scale effects in the design and fracture of composites.

Dr. Karbhari currently serves on the Civil Engineering Research Foundation (CERF) working committee on the use of composites in infrastructure. He is the American editor of the *International Journal of Materials and Product Technology*, and serves on the editorial boards of the *Journal of Thermoplastic Composite Materials*, *Processing of Advanced Materials*, and the *ASCE Journal of Cold Regions Engineering*. He has published extensively, and currently has over 80 articles in scientific journals and publications.

Joseph S. McDermott

Joseph McDermott is President of Composites Services Corporation, an independent management consulting organization founded in 1981. CSC specializes in applications development, technology assessment, and business development at all levels of the composites industry.

Eight principals are active in the company in the United States, and affiliate relationships are maintained worldwide.

Among other projects, Mr. McDermott is presently engaged by the Partnership for Plastics Progress, an activity of the Society of the Plastics Industry, Inc. to assess the environmental impact of advanced plastics molding processes for the automotive industry. In connection with this assignment and previous projects, Mr. McDermott

has visited all the commercial composites manufacturing facilities in the U.S. which supply the Big Three auto companies and their truck subsidiaries.

Prior to joining Composites Services, Mr. McDermott was chief operating officer of the Composites Institute of the Society of the Plastics Industry, the national trade association for plastics in the U.S. He began his career in 1967 as a legislative aide in the U.S. Senate.

Mr. McDermott holds a Masters degree in industrial psychology from Fordham University, New York City. He is married, with two adult sons, and resides in the New York metropolitan area.

APPENDIX B. PROFESSIONAL EXPERIENCE OF OTHER TEAM MEMBERS

The following individuals participated in the site visits in Japan, representing some sponsoring agencies for the study and the JTEC staff at Loyola College. Other sponsor representatives not participating in the Japan trip are listed in the Executive Summary.

Dana M. Granville

Dana M. Granville is a materials engineer at the Materials Directorate of the U.S. Army Research Laboratory (previously Materials Technology Laboratory), Watertown, MA. He holds a B.S. in Plastics Engineering and has completed all classroom requirements for an M.S. in Plastics Engineering at the University of Massachusetts.

Mr. Granville has 17 years experience in composite materials processing, including 13 years as a member of the DoD Manufacturing Technology Advisory Group (MTAG), and four years as manager of the Army's Manufacturing Technology (ManTech) thrust in composite materials processing.

Mr. Granville is currently the Army representative for the Office of Secretary of Defense (OSD) Materials Processing and Fabrication Committee.

Bruce M. Kramer

Bruce M. Kramer is Program Director for Materials Processing and Manufacturing at the National Science Foundation (NSF), on leave from his position as Professor of Mechanical Engineering at George Washington University in Washington, D.C.

Professor Kramer received his B.S., M.S., and Ph.D. degrees in Mechanical Engineering from the Massachusetts Institute of Technology and was Associate Professor of Mechanical Engineering at MIT before accepting his position at George Washington University.

Dr. Kramer spend the first six months of 1989 on sabbatical leave at the University of Tokyo, where he had the opportunity to visit over 25 Japanese companies, government institutions, research laboratories and universities. He retains close ties to the University of Tokyo.

Professor Kramer's research interests are in the area of materials processing, with particular interest in machining, tool design, and material development. He is the holder of two patents, the author of numerous research papers, and the recipient of

several awards, including the ASME Blackall Award for the best paper in the *ASME Transactions, Journal of Engineering for Industry* in 1982, the F.W. Taylor Medal of the International Institution for Production Engineering Research (CIRP) in 1984, and the R.F. Bunshah Award of the International Conference on Metallurgical Coatings in 1985. He was named an Outstanding Young Manufacturing Engineer by the Society of Manufacturing Engineers in 1983.

F. Xavier Spiegel

Xavier Spiegel is Associate Professor of Engineering at Loyola College in Maryland where he has taught for the last 30 years. He is a former chairman of the Department of Physics, Engineering and Computer Science, and past President of the Maryland Academy of Sciences.

His research interests include the fabrication of polymer-metallic composites, the rapid identification of metals and alloys, and the development of automated data collection systems for undergraduate research. Professor Spiegel has conducted research at the Westinghouse Electric Corporation, Johns Hopkins University, and David Taylor Research Laboratories. He is enthusiastically involved in informing groups of all ages about the mysteries of materials.

In addition, Professor Spiegel has served as the director of TTEC, a program at Loyola College funded by the Department of Transportation for research in areas of interest to the transportation community.

APPENDIX C. SITE REPORTS

Site: **Doshisha University**
Department of Mechanical Engineering
Kyoto 602, Japan

Date Visited: December 9, 1992

Report Author: V. Karbhari

ATTENDEES

JTEC:

V. Karbhari
D. Wilkins

HOSTS:

Dr. Toru Fuji — Chairman, Dept. of Mechanical Eng.

RESEARCH & DEVELOPMENT ACTIVITIES

1. Fatigue of polymer matrix composites
   - o Investigation of joints using a special rubber toughened epoxy
   - o Effects of biaxial loading in fatigue on specimens with a hole
   - o Fatigue of a woven glass composite with investigations on microstructure at the unit cell level
   - o Effects of loading and unloading durations
   - o Investigation of repeated tension-torsion loadings

2. Development of CVT belts
   - o Use of composites in continuous variable transmission belts

3. Investigation of environmental effects
   - o Acid rain -- specimens immersed in synthetic acid-rain-simulating bath and tested in fatigue -- results suggest that effect is insignificant.
   - o Effects of vacuum, dry air and oxygen rich environment on fiber strength -- results indicate that a pure oxygen environment significantly decreases S2 glass strength.

- o Effects of marine environment on performance -- the main aim is to establish accelerated testing methods. Tests are in progress, pressure being the main variable being considered.

3. Tension/torsion testing of tubes
   - o Fabricated by a wet rolling type process followed by grinding. Tests are for marine type applications.

4. Automotive transmission belts
   - o Fatigue testing of belts reinforced with aramid layers

SUMMARY

Dr. Fuji switched completely from ceramic matrix composites to polymer matrix composites in the last two to three years because of increased industrial support and because of the need to obtain specimens. His research is heavily supported by Honda, Nitta, JSR, Teijin, Shin Caterpillar Mitsubishi, and other companies and organizations that lend him equipment for tests as well as fund his research. Composite materials are supplied by courtesy of Dai-Nippon Ink & Chemicals, Asahi Fiber Glass, Toray, and other companies.

Site:	**Fuji Heavy Industries** **Aerospace Energy Division** **1-1-11, Yonan, Utsunomiya** **Tochigi 320, Japan**
Date Visited:	December 10, 1992
Report Author:	B. Kramer

ATTENDEES

JTEC:

M. Ashizawa
D. Granville
B. Kramer

HOSTS:

Mr. Masaomi Kadoya	Deputy General Mgr., Utsunomiya Plant
Mr. Takeshi Nakao	General Mgr., Research & Laboratories Dept.
Mr. Takashi Nagumo	Manager, Material Research Section, Research & Laboratories Dept.
Mr. Kenichiro Usuki	Manager, First Airframe Design Section, Fixed Wing Engineering Dept.
Mr. Toshio Sakakibara	Manager, R&D, Production Engineering Dept.

BACKGROUND

Fuji Heavy Industries started in 1917 with the establishment of the Aircraft Research Laboratory, later Nakajima Aircraft Company. The company was broken up after World War II; five elements rejoined in 1953 as FHI. FHI has four manufacturing plants in the Tokyo area, in addition to an R&D Center and the home office. Six percent of company sales are in aerospace ($453 million), and 20% of employees (3,000) are employed in aerospace.

In-house support is mainly provided for graphite/epoxy wing and fuselage structure fabrication, repair methods, and titanium-composite joint development in FHI's recent composite activity. From 1981 to 1988, MITI supported basic technology for future technologies of fiber-reinforced polymers, fiber-reinforced metals, and fabrication and design techniques for composites.

RESEARCH & DEVELOPMENT ACTIVITIES

The facility is highly production-oriented.

SUMMARY

FHI does not do CATIA simulations for the tape layer, but does simulations using its unique TLVRFY (tape layer verify) system. The facility is highly production-oriented, with the most actual production of any site visited. FHI is a Boeing subcontractor, and is required to use Boeing technology in many parts. They have learned a lot from Boeing but they now feel they could get better quality and the same technology themselves. Workers at FHI typically lay up parts according to operation sheets but they also do some memorization. Primary structures are made to layup according to operation sheets as well. They use throw-away nylon bags for autoclaving, because it reduces the expense. A laser-cut Kevlar component was shown, but water jet cutting is currently widely used since water jet cutting is considered superior.

FHI rates its composites processing as excellent compared to other Japanese industries. They do not know much about U.S. companies; only a few FHI employees have seen the production line at Boeing. They rate co-curing and honeycomb structures as their best low-cost manufacturing technologies (they include honeycomb only if they can do both the design and production).

They think that composite use in aerospace will expand, since more electronics are going into airplanes, requiring more weight savings. They feel that better design is needed; no more "black aluminum," and feel that Airbus Industries, a European company, seems to be ahead of the U.S. and Japanese companies in automated manufacturing techniques.

FHI's integral wing structure is the most complex part in the world. It took five years to develop and will be co-produced with MHI (and General Dynamics). Development was done jointly, but production will be completely separate. The most difficult aspect was developing the required bladder bag technology. Four aspects were mentioned as having potential for breakthroughs in cost reduction:

1. Reduction in material cost from $36/lb. to $10/lb.
2. Design for low cost manufacturing, using the unique characteristics of composites, including the elimination of fasteners using co-curing and filament winding
3. Automation
4. New automated manufacturing technology to eliminate autoclaving and new resin systems

The 777 co-cure horizontal stabilizer was jointly developed by FHI and Boeing. This co-cure technology is currently applied in Boeing's 777 program.

FHI indicated that scrap and bag failures are very rare. The bag material is from the U.S. and is commercial grade (the best of three available commercial grades). Our hosts stated that stitched RTM is not a good idea for cost reduction and that thermoplastic composites may reduce cost, since material cost may decrease and manufacturing methods (especially in pultrusion) have tremendous room for improvement. They observed that in the past everyone in the U.S. was excited about thermoplastics; now everyone in the U.S. is giving up on thermoplastic composites. They think there is potential, because there is no cure time. Therefore, if good processing methods can be developed and material cost is reduced, manufacturing cost can be low.

They rate, in order of importance in composites manufacturing: (1) people, (2) equipment, and (3) facilities. They are thinking about automated kitting, but only as an idea thus far.

FHI would be interested in cooperative efforts with the U.S., if they prove to be mutually beneficial.

REFERENCES

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Fuji Heavy Industries Ltd. 1992. "Aerospace FHI" (pamphlet). Japan.

Fuji Heavy Industries. 1992. *Annual Report, 1992.*

Site:	**JAMCO Corporation** **6-11-25 Osawa Titaka** **Tokyo 181, Japan**
Date Visited:	December 11, 1992
Report Author:	D. Granville

ATTENDEES

JTEC:

M. Ashizawa
J. DeVault
D. Granville
V. Karbhari
J. McDermott
D. Wilkins

HOSTS:

Mr. Yoshiro Matsuo	President
Mr. Seiji Ogawa	Executive Vice-President
Mr. Osamu Terada	General Manager, Second Manufacturing Div.
Mr. Satoru Ogasawara	General Manager, R&D Dept.
Mr. Shigeo Suzuki	Sales Manager, Marketing Dept.

BACKGROUND

JAMCO is the world's leading producer of aircraft lavatories, supplying units for Boeing 747 and 767, and McDonnell Douglas MD-80 and MD-11, and galleys for all models. Its current market share is 70% for lavatories, and 30% for galleys.

In 1952 the company began doing aircraft repair, and in 1955, aircraft component fabrication. JAMCO holds the highest levels of certification for aircraft maintenance awarded by the Japanese government; these include structural, electrical, pneumatic, hydraulic and instrumentation repair. It began making aircraft galleys in 1970. They increased production to heat exchangers and aircraft lavatories. JAMCO has extensive testing laboratories to meet Federal Aviation Administration (FAA) and American Society for Testing and Materials (ASTM) standards. Computer-aided manufacturing includes autoclave production of sandwich skin composites. JAMCO

is one of only two companies in the world capable of manufacturing jet aircraft air chillers made from thin stainless steel.

RESEARCH & DEVELOPMENT ACTIVITIES

JAMCO advanced pultrusion is used to manufacture curved T-stiffeners. This process is isobaric die roll-trusion manufacturing equipment (1-2 m/hr). Typical fabrication is two ply uni and two ply graphite fabric for each side and bottom, with PP/PET slip-sheets as separators between the split isobaric die and the product. Nylon rolls are used to guide 3" wide tape through the channel "chute" into the die, followed by variable radius takeup within the "oven" chamber.

Compression press equipment is used for continuous sandwich skin laminate structures using a honeycomb core.

Lavatory and galley expenditures are highest in the machining, trimming, and assembly costs. Current cost of a lavatory is approximately $30,000 to $40,000. The weight is approximately 250 lbs. JAMCO uses a "streamlined" assembly approach. Lavatory assembly stations are set up so that each worker has the responsibility for two or three assembly details. More experienced workers are at the end of the assembly cycle; they are skilled in all tasks and quality checks. Workers keep a running record of all engineering change orders, drawing changes, sub-assembly changes, and fabricating, machining, and trimming errors. JAMCO hopes to further investigate self-extinguishing low-exotherm thermosetting resins, advanced pultrusion methods, and lightweight sheet molding compounds (SMC) for aircraft markets.

SUMMARY

JAMCO has excellent data processing, manufacturing, planning, and inventory control systems. It has 52 CAD terminals, eight for 3-D solid modelling, the remainder for 2-D. They do not use CATIA as Boeing does, but use another less sophisticated but compatible system. Their CAD is adaptable to CAM so that information is transferrable to the shop floor. CAD data files are essential for later maintenance of the lavatories, and as a record for Boeing. Engineering has an on-line communications network with Boeing. Manufacturing drawings are kept separately from design drawings but the skilled workforce has no trouble reading design drawings. Shop people are regarded eminently qualified to address quality issues and to assess better ways of building the product. Scrap is approximately 10% for all composite lavatories and ways to recycle scrap are being investigated since waste removal costs are very high. Three autoclaves are in operation, but no modern feedback controllers are used. Disposable vacuum bags are used but JAMCO is evaluating the newer re-usable elastomeric cauls and bags and bag

sealing methods. Material (pre-preg and core) quality is "bought" (in specs) from the suppliers. No differential scanning calorimetry or other chemical characterization is used, but there are many tests and visual checks for the finished product quality after processing.

REFERENCES

JAMCO. 1992. *Annual Report.*

JAMCO AMERICA. 1992. "Component Technology in Flight" (brochure).

Site:	**Kawasaki Heavy Industries** **Aerospace Engineering Dept.** **1 Kawasaki-chome, Kakamigahara-shi** **Gifu Prefecture 504, Japan**
Date Visited:	December 8, 1992
Report Author:	B. Kramer

ATTENDEES

JTEC:

I. Ahmad
M. Ashizawa
J. DeVault
D. Gill
B. Kramer
X. Spiegel

HOSTS:

Mr. Kohmei Kawaji	Sr. Mgr., Aerospace Eng. Dept., Aerospace Group
Mr. Kohki Isozaki	Associate Dir., General Manager of Aerospace Eng. Div. & Space Systems Div., Aerospace Group
Mr. Motoaki Yanase	Mgr. of MR&D Section, Manufacturing Eng. Dept., Gifu Aircraft Div.
Mr. Minoru Noda	Mgr. of Materials & Process Engineering Section, Aerospace Eng. Dept., Aerospace Eng. Div., Aerospace Group
Mr. Hirotoshi Nakayama	Mgr. of Structures & Materials Research Section, Aircraft Research Lab., Gifu Technical Institute
Mr. Hisao Sayanagi	Manager of Structure Eng. Section, Aerospace Eng. Dept., Aerospace Eng. Div., Aerospace Group

BACKGROUND

Kawasaki started assembling aircraft in 1923. The company separated from the Kawasaki Dockyard as an independent company in 1937.

The Aerospace Group consists of seven divisions (see Figure KHI.1). The principal composite products manufactured are shown in Figure 1.2 (Chapter 1, p. 6). KHI's major equipment for composites manufacturing is indicated in Table KHI.1.

RESEARCH & DEVELOPMENT ACTIVITIES

KHI has developed a low cost method for manufacturing an Ω-type stringer, using a teflon rod insert and silicone rubber tooling.

There is new technology for producing super-composite bolts (see Figure KHI.2). The unique feature is that the fibers bend into the thread space, vastly increasing shear strength. They have a 4.8:1 specific strength advantage versus high strength steel.

KHI has developed technology for producing sine wave stiffeners using a low CTE, cast steel tool on the outside and silicone rubber on the inside.

SUMMARY

Our KHI hosts preferred not to rate their company relative to others due to a lack of information. They felt that composites raw material costs should be reduced by about 50%, and indicated that they tried to get structures business from the U.S. and Europe, but that their quotes were too high.

When the JTEC team observed that KHI's parts were highly integrated by co-cure; our hosts agreed, but added that they needed excellent craftsmanship to get good yield.

The team noted three items of particular interest:

1. The use of integral tool heating in the high temperature (450°C), high pressure (20 kg/cm^2) autoclave

2. The use of integral tool cooling (air and water) in the autoclave

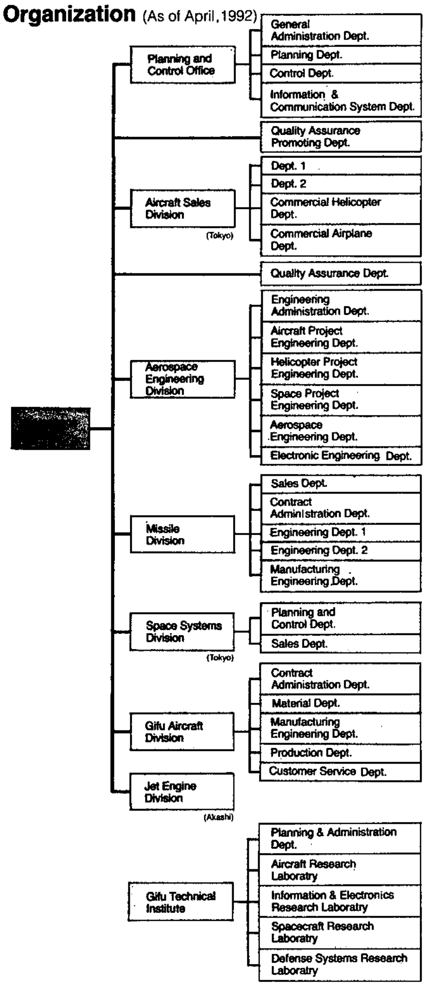
3. The Ω-stiffener manufacturing process

The emphasis on new process development was on tough resins and high temperature resins.

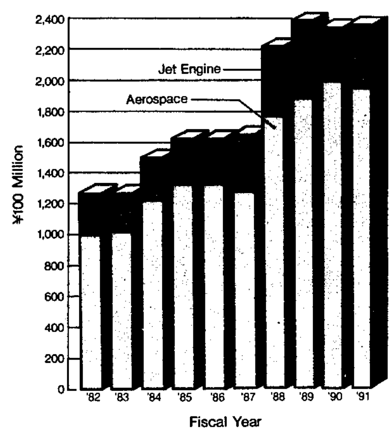
Historical Highlights

1878 Mr. Shozo Kawasaki founded a shipyard in Tsukiji, Tokyo (later moved to Kobe).
1896 Kawasaki Dockyard reorganized into a stock company.
1923 Aircraft assembly plant constructed at Kakamigahara.
1937 Kawasaki Aircraft Co. separated from Kawasaki Dockyard as an independent enterprise.
1954 Business restarted under the name of Kawasaki Aircraft Co. through a merger of the old Kawasaki Aircraft Co., Kawasaki Machine Industries and Kawasaki Gifu Works.
1969 Kawasaki Heavy Industries established through a merger of the Kawasaki Dockyard Co., Kawasaki Aircraft Co., and Kawasaki Rolling Stock Mfg. Co.

Organization (As of April, 1992)



Sales



Manufacturing Status of Principal Products (As of April 1, 1992)

Type	Kind of Aircraft	Period of Manufacture	Remarks
Fixed-Wing Aircraft	T-33A jet trainer	1955–58	210 planes
	P2V-7 ASW patrol airplane	1958–65	48 planes
	F-104J jet fighter	1961–67	207 planes (co-production)
	YS-11 medium transport airplane	1962–72	182 planes (joint production)
	P-2J ASW patrol airplane	1967–78	83 planes
	F-4EJ jet fighter	1969–81	138 planes (co-production)
	C-1 medium transport airplane	1970–81	31 planes
	P-3C ASW patrol airplane	1978–	75 planes
	F-15J fighter	1978–	151 planes (co-production)
	Boeing 767 passenger airplane	1978–	451 planes (co-production)
	T-4 Medium Trainer	1985–	76 planes
	EP-3 Utility Airplane (EW)	1988–	2 planes
Helicopters	Kawasaki-Bell 47 helicopter	1952–75	439 planes
	Kawasaki-Vertol 107 IIA helicopter	1963–89	160 planes
	Kawasaki-Hughes 369 helicopter	1969–	315 planes
	Kawasaki BK117 helicopter	1982–	359 planes
	CH-47 helicopler	1986–	35 planes
Missile	Type 64 anti-tank missile	1964–	(ATM)
	Type 79 anti-landing craft/anti-tank missile	1979–	(H-ATM)
	Type 81 TAM SAM	1981–	(SAM-1)
	Type 87 anti-tank missile	1987–	(M-ATM)
	Type 89 Fighting Vehicle Missile Launcher	1989–	(FV-ATM)
	Type 91 Portable SAM	1991–	(SAM-2)
Space Equipments	Geodetic Satellite	1986–	—
Repairs	Fixed Wing	1953–	4,044 planes
	Helicopter	1954–	2,036 planes

Figure KHI.1. Organization Chart (Courtesy of Kawasaki Heavy Industries, Ltd.)

Table KHI.1
KHI Facilities for Composite Products

Autoclave
Automatic Tape Layup Machine
Automatic Prepreg Cutting Machine
Filament Winder
Honeycomb Core Cutting Machine
Water-Jet Knife
X-Ray Inspection Equipment
Ultrasonic Inspection Equipment

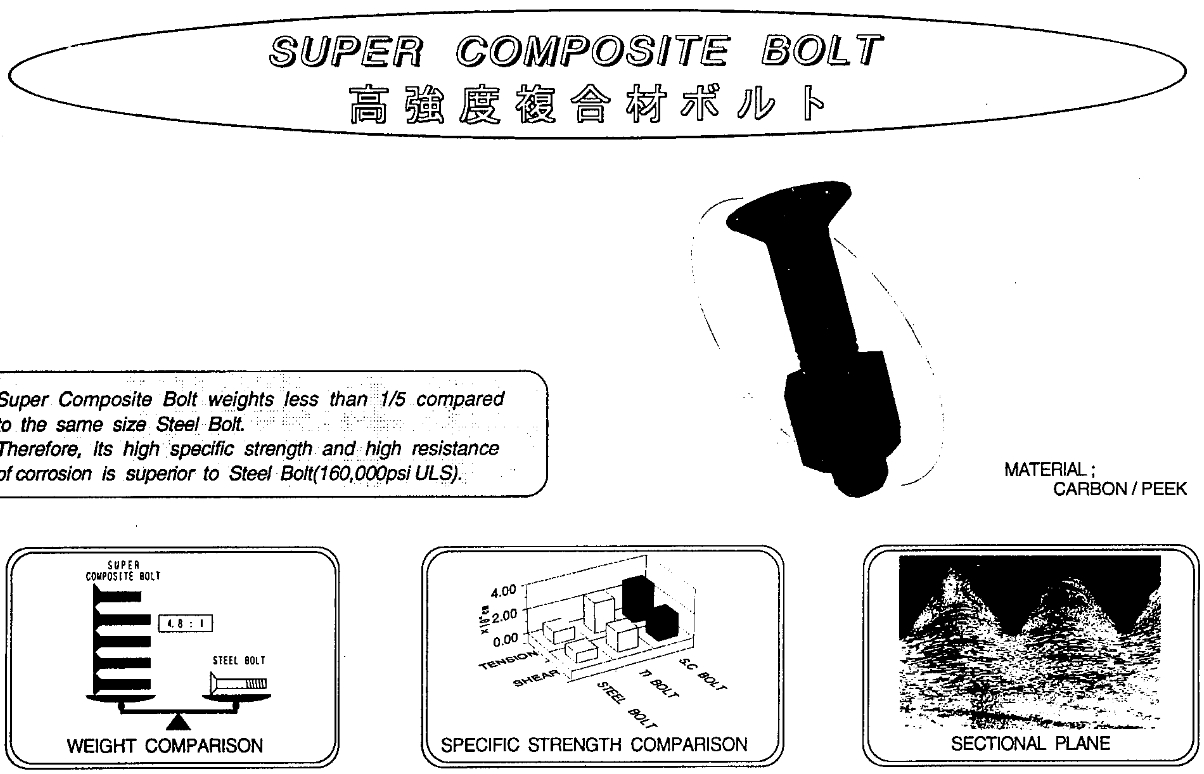


Figure KHI.2. Super Composite Bolt -- expected for future use in the sea, ground, air, space and so on. KHI expects great activity in all fields.

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Kawasaki Heavy Industries Ltd., Aerospace Group. 1991. "Advanced Material Products in the Aerospace Field" (brochure). Japan.

------. 1992. "KHI's Capability for Composite Structure" (viewgraph).

Kawasaki Heavy Industries, Ltd. 1992. "Gifu Works" Cat. No. 5V0071 (brochure). Japan.

Site: **Kyoto Institute of Technology (KIT)**
Matsugasaki, Sakyo-ku
Kyoto 606, Japan

Date Visited: December 9, 1992

Report Author: B. Kramer

ATTENDEES

JTEC:

J. DeVault
B. Kramer

HOSTS:

Dr. Zenichiro Maekawa	Professor, Faculty of Textile Science
Dr. Eng. Hamada Hiroyuki	Assoc.Professor, Faculty of Textile Science
Mr. Akihiro Fujita	Research Assoc., Faculty of Textile Science
Gabriel O. Shonaike, Ph.D	Faculty of Textile Science

BACKGROUND

Professor Maekawa's research group in composites is the largest in Japan, with 40 industry affiliates, seven doctoral candidates, nine masters candidates and 12 bachelors candidates.

RESEARCH & DEVELOPMENT ACTIVITIES

Professor Maekawa summarized the research projects in his laboratory (see Table Kyoto.1). The JTEC team was provided with an extensive collection of recent papers and research reports (mostly in Japanese). There is extensive work in braiding, with KIT performing braiding, industry conducting curing, and KIT doing characterization. A particular emphasis is on co-mingled yarn systems. They hope to organize an international symposium on fiber-resin interface studies in Japan in 1998, to complement an annual symposium on the subject in Japan.

Table Kyoto.1
Research Programs in Dr. Maekawa's Department

RESEARCH PROGRAMS
Fabrication and mechanical properties of 3-D composite materials
Reliability improvement on mechanical properties and fracture behavior of ACM
Durability evaluation of composite materials under hot water and acidic environment
Damping properties of FRP with modified resin and hybrid reinforcement
Measurement of fiber orientation process in thermoplastic composites
Evaluation of the interfacial properties in GFRP
Melt flow analysis of injection molding
Non-destructive evaluation by AE
Static and fatigue properties of mechanically fastened CFRP
Crushing properties of CFRP and GFRP

SUMMARY

KIT is conducting an impressive range of research activities, with strong modeling and characterization efforts and very strong and effective links to industry. The research group appears to be limited by a severe shortage of space and, particularly, of space that is of sufficient quality to perform the most demanding composites processing applications.

REFERENCES

Tokyo Institute of Technology. 1992. PM KIT.

Site:	**Mitsubishi Electric Co. (MELCO)** **Sagami Works** **Materials & Electronic Devices Laboratory** **1-1, Tsukaguchi-Honmachi 8-chome** **Amagasaki, Hyogo 661, Japan**
Date Visited:	December 11, 1992
Report Author:	B. Kramer

ATTENDEES

JTEC:

M. Ashizawa
J. DeVault
D. Gill
B. Kramer

HOSTS:

K. Murayama	Materials & Electronic Devices Lab
S. Yamashita	Materials & Electronic Devices Lab
T. Inoue	Kamakura Works
S. Utsunomiya	Sagami Works
K. Kawakami	Sagami Works
H. Shimodaira	Sagami Works

BACKGROUND

MELCO started producing glass & fiber-reinforced radar domes in 1955 and began applying composites to satellites in 1970. The company is now one of the biggest satellite manufacturers in Japan. It develops all of its own composites technology for satellites. A synthetic aperture radar launched in 1992 has eight panels, 2.2 m x 1.4 m each with 1 mm form accuracy. The Intelsat VII, C-band antenna is 2.44 m diameter, with 0.15 mm accuracy. Heat pipe panels are produced up to 2.4 m x 2.8 m in size. Large solar panel arrays are also produced.

RESEARCH & DEVELOPMENT ACTIVITIES

Continuously Formed Graphite/Epoxy Composite Tubes for Large Space Structures
(MITI research project -- approximate cost of $1 million for the machine)

The machine combines filament winding and pultrusion with high E fiber and epoxy resin, achieving 60% fiber volume fraction. Production rate is 1-5 m/hr. It uses prepreg tape, approximately 50 meters on each tape spool.

Reinforcement Architecture for Fiber-Reinforced Composites

MELCO currently uses 2.5-D preforms. The 3-D composites research consortium was started five years ago with 10 researchers from five companies (NSC, Toyoda, Mitsubishi Rayon, and Arisawa and MELCO) and $16 million in funding for six years (70% government & 30% companies).

Braiding

It is believed that the most promising technologies are four-step braiding and four-axis and five-axis braiding. Mr. Murayama is very knowledgeable about braiding. MELCO has good capabilities in cylindrical braiding and has a parabola weaving machine that is patented. A 3-D knitting machine is under development by Asahi Kasei.

SUMMARY

Our MELCO hosts stated that they cannot rate their company relative to other companies, since they have not seen other companies. They use CAD/CAM, and their best manufacturing technologies are accurate filament winding (better than anyone else) and very lightweight structures. They think there may be a good future for composites, if applications can be developed. RTM is a potential breakthrough technology in the mid-volume area (not refrigerators). The main problem in 3-D weaving is production rate and no solution is in sight; 2.5-D might provide a partial solution.

MELCO uses supplementary oil heating on autoclave tooling and produces very flat solar cell panels with excellent seams. Our hosts expressed the view that design for the total system of composites is very important, since conventional design systems are oriented towards metals. They feel the key element is more imaginative, creative people.

Our hosts indicated that U.S.-Japanese cooperation could help increase the use of composites and they are interested in continued cooperation. They have good

cooperation with their suppliers, but communications with other manufacturers is on a person-to-person basis only.

For widespread use, low fiber cost is not critically needed. It is more important to reduce finished cost to 2-3 times raw material cost, instead of 10-50 times.

REFERENCES

Mitsubishi Electric Co. 1992. "The Sagami Works 1992 Corporate Profile."

------. "Space Activities" (brochure).

Site: **Mitsubishi Heavy Industries**
Research Division
Nagoya Aerospace Systems Factory
10 Oyemachi, Minato-ku
Nagoya-shi, Aichi-ken 455, Japan

Date Visited: December 8, 1992

Report Author: B. Kramer

ATTENDEES

JTEC:

D. Wilkins
M. Ashizawa
J. Devault
D. Gill
I. Ahmad
X. Spiegel

HOSTS:

Mr. T. Tanioka	Director, Eng. Research Dept.
Mr. T. Ikeda	Asst. Dir., Aircraft Engineering Dept.
Mr. Y. Yamaguchi	Asst. Dir., Engineering Research Dept.
Mr. K. Ogasawara	Manager, Production Dept.
Mr. T. Yamamoto	Manager, Engineering Research Dept.
Mr. Shiraishi	

BACKGROUND

The Nagoya works employs 4,593 people. Mr. Shiraishi indicated that almost anything could be discussed at this meeting, except areas related to Japanese Defense Agency projects.

Mr. Ogasawara indicated that advanced composites work at MHI started in 1969. As a result, MHI is the world leader in co-curing technology, which is needed to reduce assembly cost.

General applications include the co-curing of very large and complex parts, including a new fighter wing torque box which is 160" by 80". It took 5 years to

develop the technology to produce the wing torque box by co-curing. The part is autoclaved in the biggest unit in Japan: 18' diameter, 51' long, within 200 psi, 800°F capability.

RESEARCH & DEVELOPMENT ACTIVITIES

1. 3-D composites. Efforts are to improve interlaminar shear strength. They do the weaving for the project in-house.

2. Resin-transfer molding (RTM). It was indicated that they were investing "almost significant" research resources in the project. When asked what the biggest challenge in RTM was, they indicated that it was the resin. The JTEC team indicated that it thought weaving was the biggest challenge. However, our hosts replied that they have a low-cost method for manufacturing the preform. They also have many specialty weavers in Japan working on preforms. U.S. companies are coming to Japan for weaving technology.

3. Film infusion.

4. Material development. The emphasis is on thermoplastics and high temperature resins.

MHI representatives listed five key approaches to co-curing technology:

1. Finding the applicable range of co-curing. MHI engineers calculate the design/manufacturing/quality assurance (QA) trade-off for each part in order to optimize resources. When asked how the scrap rate is estimated for the model, they indicated that they assumed zero scrap. They have an effective repair method for fixing the defects they get. When asked about bag leakage, they indicated it almost never happens. For instance, only one failure in 240 speed brakes.

2. Assuring the strength of the co-cured interface for in-plane shear, tension and peel.

3. Minimizing thermal deformation. Finite element methods (FEM) analysis is used to adjust parts deformation.

4. Assuring achievable tolerance.

5. Assuring effective repair methods.

MHI employs five key methods for improving co-curing:

1. Each detail part is compacted before co-curing the assembly to remove air and water, to adjust the resin viscosity and to control the dimension and/or shape of the part. The parts are non-destructive evaluation (NDE) inspected by ultrasound after hot compaction.

2. A reliable, leak-free bagging system is used. The MHI system is made from unreinforced silicon rubber, reusable for 20 cycles. The company used to buy bagging rubber from a U.S. material supplier, but now makes its own. It has developed its own zip-lock system for bagging.

3. Dimensional stability is assured to minimize warpage. MHI uses invar tooling.

4. Pressure is transferred directly to the part using a molded bladder bag that has the same shape as the part.

5. Temperature uniformity is assured by uniform gas flow in the autoclave.

The MHI staff feels that 80% of their success is in the tool, but indicated that this assumes the use of high quality labor. For tooling research, film pressure transducers are used in the autoclave.

MHI is engaged in the following cost reduction activities:

1. Cooperation between research, design, manufacturing, and Q/A

2. Manufacturing development incorporating a zero-defect goal and emphasizing step-by-step development

3. Low cost manufacturing technology including:
   a. Automated cutting and nesting
   b. Automated layup
   c. Computer-controlled cure with temperature and pressure sensing but no supplemental tool heaters
   d. Net trim before cure with an NC trimming machine

SUMMARY

MHI representatives indicated that prepreg cost is important, that filament winding, pultrusion and thermoplastic composites are not used in production, and that CATIA data are shared by designers, automated layup, and tool fabricators. Our hosts expressed the view that a 50% decrease in cost could be attained with accumulated minor improvements, that no major breakthroughs were on the horizon, and that MHI

has a special device (an intensifier) to prevent bleeder mark-off, but that they cannot discuss it. The method involves the use of carbon fiber slip-sheets.

They indicated that MHI wingbox technology has been transferred successfully to General Dynamics and that they do not use long, discontinuous fibers.

Composite organizations mentioned included JSCM and JSAMPE. Professor Maekawa of Kyoto Institute of Technology was mentioned as one of the leading university researchers.

Site: **Mitsubishi Kasei Corp. (MKC)**
Research Center
1000, Kamoshida-cho
Midori-ku, Yokohama 227
Japan

Date Visited: December 7, 1992

Report Author: D. Granville

ATTENDEES

JTEC:

J. DeVault
D. Granville
J. McDermott
D. Wilkins

HOSTS:

Dr. Yasuhiro Ohmura	General Manager, Material Science Research Sector
Mr. Takao Uematsu	Chief Research Scientist, Advanced Composite Materials Laboratory
Mr. Shigeki Tomonoh	Research Scientist, Advanced Composite Materials Laboratory
Dr. Tohru Imanara	Sr. Research Scientist, Advanced Composite Materials Laboratory
Mr. Junichi Goto	Manager, Research Planning Dept.

BACKGROUND

Mitsubishi Kasei is involved in six basic areas of technology: carbon chemistry, inorganic chemistry and metallurgy, organic chemistry, polymer chemistry, electronics, and biotechnology. MKC services civil engineering and the sporting goods markets as well as the pharmaceutical, agricultural, and communications markets. This is an innovative corporation with diverse interests from superconductors to carbon fiber and biotechnology.

A joint venture with U.S. company Fiberite/ICI dissolved in October of 1992.

RESEARCH & DEVELOPMENT ACTIVITIES

MKC's research activity in advanced polymer composites includes materials-pitch based carbon fiber, formulations of thermoset resins, thermoplastics resin and prepreg (pan-based CF, pitch based CF, GF, aramid fiber).

In pitch carbon fiber development, MKC markets "Dialead" (500 tons/year), to make prepregs and printing press rolls. It is one of the three largest manufacturers of pitch based carbon fiber in Japan. They start at the raw feedstock level with coal tar (pitch coke, needle coke, dialead) which is incorporated into metals, plastics and cement. Several application technologies were developed or are being developed for civil engineering and architecture: curtain wall, rod for prestressed reinforcement, smoke stack reinforcement, slab retrofitting reinforced with CF UD tape and also special resin systems for reinforcement. The Kyushu Prince Hotel has cement walls using graphite-reinforced cement. Another innovation is in smoke stack applications where the top 1/3 is reinforced with pitch-based graphite. Pre-preg uni-tape is laid down along the stack axis, then overwrapped with wet strand reinforcement at a low temperature cure. Other applications include 8 mm diameter carbon fiber reinforced plastic (CFRP) rods (thermoplastic) for anchors in construction (often prestressed) and hexagonal honeycomb pontoons.

Structural RIM has applications for electric motor scooters and also for large parts with high strength at high speeds. From near net-shape parts (30% V_f) using epoxy/acrylic hybrid resins, a scooter frame was developed which replaced a steel frame and fairings with a 40% weight savings. Other applications are being pursued for sporting goods (lamination technology for golf shafts and fishing rods) and industrial markets (roll manufacturing technology and railway components). Not much work is being done on automotive applications, but they are doing work on trains.

SUMMARY

Business units fund 80% of MKC research activities, specifically in pitch-based carbon development, pre-preg, chopped fiber etc. MKC developed the SRIM process with special hybrid resin systems, and successfully applied the modeled product to the structural body of an electric scooter, the design and assembly of which were performed at Tokyo R&D. MKC is the developer and supplier of pitch carbon fiber (chopped and continuous) and epoxy/acrylic resins. It is developing the processing science in structural RIM, as well as the processing science and product development in CFRPs (PC, PBI, TP molding compounds), scooter frames, golf shafts, composite rolls, cement walls, and composite rod for construction anchors.

REFERENCES

Mitsubishi Kasei Corporation. "DIALEAD CFRC (Carbon Fiber Reinforcement Cement)" (brochure).

------. "DIALEAD - Coal Tar Pitch Carbon Fiber". Mitsubishi Kasei Corp. and Mitsubishi Kasei America Inc. California Office (viewgraphs).

------. "I am MITSUBISHI KASEI" 1991-92 Annual Report (brochure).

------. "Mitsubishi Kasei - CFRP LEADLINE Carbon Fiber Rod" (brochure).

------. "Mitsubishi Kasei DIALEAD:Coal Tar Pitch-Based Carbon Fiber" (brochure).

------. "Mitsubishi Kasei, Ohbayashi Corporation - New Method with New Materials - Carbon Fiber Reinforced Earthquake-Resistant Retrofitting" (brochure).

------. "Mitsubishi Pitch Carbon Fiber - Application: Carbon Fiber Reinforced Thermosetting Plastics" (brochure).

------. "Mitsubishi Pitch Carbon Fiber - Application: Carbon Fiber Reinforced Thermo Plastics" (brochure).

------. "Mitsubishi Pitch Carbon Fiber - Application: Carbon-Carbon Composite" (brochure).

------. "Mitsubishi Pitch Carbon Fiber - Application: Metal Matrix Composite" (brochure).

------. "RESEARCH & DEVELOPMENT - Mitsubishi Kasei Corporation," with Corporate Data enclosed, as of July 1, 1990 (brochure).

Reprint of "Advanced Materials for Future Industries: Needs and Seeds." from *Proceedings of The Second Japan International SAMPE Symposium and Exhibition*, Chiba, Japan, December 11-14, 1991 by the Society for the Advancement of Material and Process Engineering," Abstract by Shoichi Sato, Tohru Imanara, Naomi Iketani, and Takao Uematsu, "A New Resin System for S-RIM," pp. 44-50.

Site:	**Mitsui Toatsu Chemicals, Inc.** **2-5, Kasumigaseki 3-chome** **Chiyoda-ku, Tokyo 100** **Japan**
Date Visited:	December 7, 1992
Report Author:	D. Granville

ATTENDEES

JTEC:

J. DeVault
D. Granville
J. McDermott
D. Wilkins

HOSTS:

Mr. Moto Kawamata	Assistant Dir., Corp. R&D Administration Dept.
Dr. Akihiro Tamaki	Deputy Dir., Central Research Institute
Mr. Sadayuki Esaki	Manager, TPI Development Dept.
Mr. Norifumi Ito	Director, Polymer Research Laboratory
Mr. Masahiro Masutani	Chief Research Coordinator, R&D Coordination Office, Central Research Inst.

BACKGROUND

Mitsui Toatsu Chemicals is a privately owned company with 55.4% of their business in commodity products (plastics, fabricated plastics, industrial chemicals, and industrial fertilizers), 15.4% in fine chemicals (pharmaceutical, agrochemicals, and dyestuffs), and 22.3% in specialty products (urethanes, industrial resins, building materials, electronic materials, and performance polymers). The company started R&D work on advanced thermoplastic prepregs with hot melt impregnation in 1983. Twenty-five percent of the workforce is in R&D. The goal of the company is to expend 60% of the R&D budget in specialty chemicals and materials. They participate in joint R&D with other Pacific rim counties, and have collaborative programs with universities in the U.S. (MIT, Wisconsin, and Univ. of Washington), as well as with Fuji Heavy Industries and the Society of Japanese Aerospace Companies. Work for the High Speed Civil Transport (HSCT) program is with BASF and Boeing. Their program with Fuji Heavy Industries (FHI) for the National

Aerospace Laboratory (NAL) is in molded PIX/T-800 pre-preg for fatigue testing; they also have another program for a fusion bonding system with FHI sponsored by SJAC.

RESEARCH & DEVELOPMENT ACTIVITIES

Mitsui Toatsu Chemicals is developing catalysts for epoxy synthesis, aromatic polyimide special plastic lens monomers (refractive index 1.6), heat-sensitive coated papers, and amorphous silicon solar cells. They have developed PIX (TP Polyimide) CF pre-preg tape for automated composite materials (ACM), and will also make molding compounds for injection molding (388°C melting point and good moldability). At the time of the JTEC team's visit, they were in the process of developing PP, PS, AS, ABS, Barex 210 (acrylonitrile barrier resin), PES, PEEK processors, and urethanes; they were planning to develop compact discs by April 1993. They have developed TPI adhesive for fusion bonding at Mitsui and constructed panels for aircraft fuselages at Fuji, and have developed an improved interface GF/PP pre-preg with special surface treatments for low cost applications (well suited for automotive applications).

Professor Seferis of the University of Washington is working on PIX development.

SUMMARY

This is an excellent company structure for commodity plastics, engineering resins (TP & TS), and composites using primarily carbon and glass. They are backed by well-staffed analytical, characterization, and testing laboratories. The in-house analytical research department has an excellent modeling capability. Their customer base is broad (aerospace, industrial, construction, automotive, sporting goods, and marine). There are extensive international agreements of cooperation with U.S. companies and universities. Training and extensive cooperation is practiced with both their customers and partners.

REFERENCES

Mitsui Toatsu Chemicals, Incorporated. "Mitsui Toatsu Chemicals, Inc. Annual Report, April 1991-March 1992."

------. "Mitsui Toatsu Chemicals, Inc. Tokyo, Japan," as of March 1992.

------. "Research & Development - Mitsui Toatsu Chemicals, Inc."

Site: **MITI Headquarters**
Bureau of Machinery and Info. Industries
Aircraft and Ordnance Division
3-1, Kasumigaseki 1 chome, Chiyoda-ku
Tokyo 100, Japan

Date Visited: December 7, 1992

Report Author: B. Kramer

ATTENDEES

JTEC:

M. Ashizawa
D. Granville
V. Karbhari
B. Kramer
X. Spiegel

HOSTS:

Mr. Keisuke Saito — Deputy Dir., Aircraft Ordnance Division

BACKGROUND

The Ministry of International Trade and Industry (MITI) was originally established as the Ministry of Commerce and Industry in 1949 with the mission of developing the Japanese economy and industry.

Figure MITI.1 shows an organizational chart. In brief, it indicates that 12,447 people do the work for MITI. Within MITI, the Machinery and Information Industries Bureau (one of seven internal bureaus, employing a total of 2,263 people) handles the manufacturing-related aspects of composites, while the Basic Industries Bureau handles the materials aspects.

The Machinery and Information Industries Bureau employs about 200 people. Within this bureau is the Aircraft and Ordnance Division, which employs 12 people.

RESEARCH AND DEVELOPMENT ACTIVITIES

Mr. Saito is a policy expert. Therefore, his presentation emphasized policy matters.

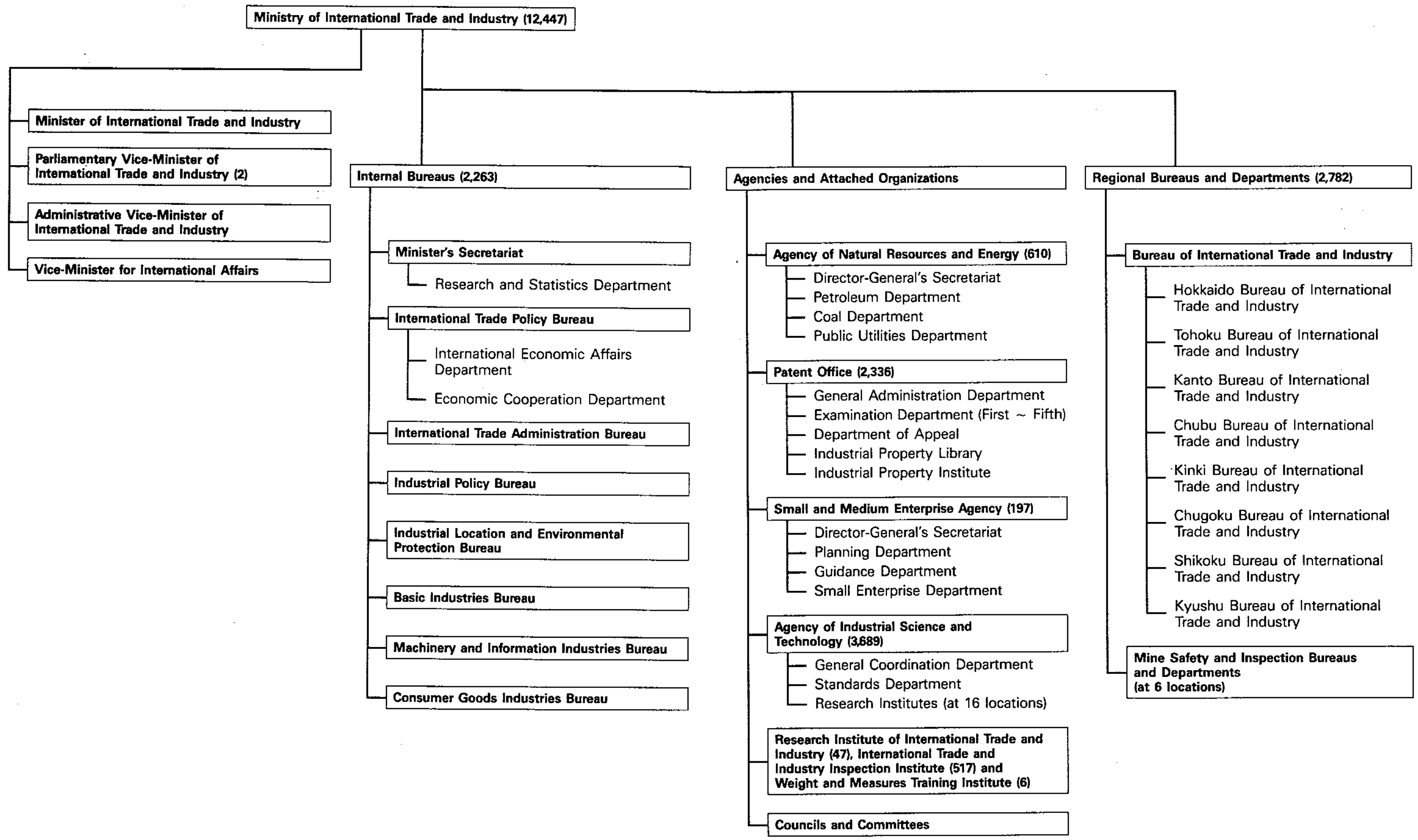

Figure MITI.1. Organization of MITI - "MITI is organized so as to facilitate the effective implementation of concrete measures in line with the Ministry's basic policies (MITI, pp. 6 & 7)."

SUMMARY

Utilization of dual-use technologies. Dual-use technologies means that the export of a technology is allowed if it has been designated for civilian use, or is being used already by the Japanese industry for civilian purposes. Otherwise, export of technology is decided on a case-by-case basis by the International Trade Administration Bureau, Export Division, indicated in Figure MITI.2.

When asked which part of MITI organized cooperative projects, it was indicated that each bureau has its own R&D budget. In addition, the Agency of Industrial Science and Technology (3,700 people) runs 16 regional institutes (see Figure MITI.1), the majority of which are located in Tsukuba City. Four years ago, for the first time, foreign companies were invited into an aircraft engine project (GE, Pratt and Whitney, SNECMA and Rolls Royce) and these four received Japanese funds.

It was indicated that the aircraft industry in Japan is 75% military, with a declining defense budget (see Tables MITI.1 - MITI.3); therefore, output is decreasing in 1992. Regarding MITI projects in aerospace, funds are only available for international cooperation: Japanese companies cannot get funding unless they have foreign partners. Current projects include the Boeing 777, the V2500 hypersonic (Mach 4-5) engine (with P&W, Rolls Royce, Fiat, and MTU [Germany]). Plausible future projects include a 600-800 passenger super-jumbo jet, an SST, or a small, 50-100 passenger aircraft.

Table MITI.1
Military/Civil Demand
(¥ billion)

YEAR	TOTAL OUTPUT (A)	MILITARY (B)	CIVIL	RATIO* (B/A)
1988	661	523	138	79.1%
1989	731	558	173	76.3%
1990	802	601	201	74.9%
1991	851	639	212	75.1%

* The ratio is around 35% in the U.S. and 65% in England.

We asked what was MITI's policy in dealing with excess capacity in composites and were told that the official policy is that composites are very important.

International Trade Administration Bureau

- Director-General
  Deputy Director-General
- General Affairs Division
  - Trade and Foreign Exchange Affairs Office
  - Inspection and Design Policy Office
- Export Division
  - Security Export Control Office
  - Strategic Commodities Export Inspection Office
- Import Division
  - Director for Control of International Trade in Endangered Species
- Agricultural and Marine Products Division
- Foreign Exchange and Trade Finance Division
- International Trade Insurance Division (Policy Planning)
  - Director for International Trade Insurance Coordination
  - International Trade Insurance Administration Office (Short-term Insurance)
  - Financial Affairs Office
  - Information System Office
- International Trade Insurance Division (Long-term Insurance)
  - Overseas Investment Insurance Office

Figure MITI.2. International Trade Administration Bureau (MITI, p. 10)

Table MITI.2
New Contracts for Combat Equipment (Defense Agency)
(¥ billion)

	1990	1992	GROWTH RATE
	1,073	865	-19.4%
(Related to Aircraft)	360	270	-24.9%

Table MITI.3
Output in the Japanese Aircraft Industry

YEAR	OUTPUT (¥ billion)	GROWTH RATE	EMPLOYEES
1988	661	1.2%	27,913
1989	731	10.5%	28,913
1990	802	9.7%	28,810
1991	851	6.2%	29,160
1992	800	-6.0%	29,160

REFERENCES

Ministry of International Trade and Industry. "MITI." Japan.

Site:	**National Research Institute of Materials and Chemical Research (NIMC)** **Structure Technology Dept.** **MITI/AIST** **1-1-4, Higashi, Tsukuba-shi** **Ibaraki-ken 305, Japan**
Date Visited:	December 10, 1992
Report Author:	D. Granville

ATTENDEES

JTEC:

D. Granville
V. Karbhari

HOSTS:

Ryuichi Hayashi	Director, Structure Technology Dept.

BACKGROUND

A major reorganization of MITI labs and overhaul/reexamination of objectives in all technology/industrial projects funded by MITI was planned for 1993. Projects typically run approximately eight years. At the half-way point of the project, a full evaluation occurs (a major review) to warrant further funding. Also, two reports are given per year as part of the review process. In addition, a symposium is held annually to review all projects, with papers published in the proceedings.

MITI receives proposals from universities, national institutes, and industry for review and selection by Technical Committees for each technology (six year cycle).

RESEARCH & DEVELOPMENT ACTIVITIES

Two national projects:

1. R&D on Composite Materials, 1981-1988

2. R&D of Hi-Performance Materials for Severe Environments, 1989-1996; approximately 200 researchers are involved, includes work with c/c, intermetallics, and fiber-reinforced IMC matrix composites.

Table NIMC.1
Budgets
(¥ Million)

	1989	1990	1991	1992
National Research Institute	50	104	135	-
New Energy Development Org.	251	897	1,564	-

Japan was the host of the Joint Symposium of Japan-Euro Exchange on Composite Materials and High Performance Materials for Severe Environments in June 1993.

Fiber reinforced TiAl IMC composites at NIMC are now using Textron SiC (CVD) fibers and in the future will use Japanese Nicalon or Tyrano fibers to optimize prop's in composite development. Research work is also done in cooperation with American universities and institutions such as Georgia Tech.

NIMC has the VAMAS Projects (polymer composites) with ISO and JIS, including

- Gas sensors project for environmental monitoring using nano-composites
- EMI-shielding materials in composites
- Polymer conductive paints, use of carbon fiber & mica

SUMMARY

Most of the discussion covered the organization's background and structure, and its university and industrial participants. Present funded work covers much of the fundamental characterization, surface analysis work, and testing of c/c and intermetallics, as well as the evaluation of carbon fiber reinforced TPs. A tour was provided of their mechanical test lab, where a crack propagation and compliance experiment was in progress on an Instron machine to evaluate T800/epoxy & PEEK laminates (materials to be used on the Boeing 777). Also, a robotics lab, olfactory lab, and depth perception lab were briefly presented to demonstrate their interest in addressing artificial means of developing human sensory perception.

A processing lab with a Japanese-made autoclave (up to 350°C, 300 psi pressure) and a 2' x 2' compression press capable of very fast cool-down rates (for evaluating crystallinity growth and size of TPs) was also visited.

REFERENCES

Bathias, Claude and Masuji Uemura, editors. "Advanced Composite Materials: New Materials, Applications, Processing, Evaluation and Databases," *Proceedings of the 1st France-Japan Seminar on Composite Materials*, Paris-Le Bourget (March 13-14, 1990). Paris:SIRPE Publishers.

Site: **National Research Institute of Materials and Chemical Research (formerly Research Institute for Polymers & Textiles)**
Polymer Composites Laboratory
MITI/AIST
1-1-4 Higashi, Tsukuba-shi
Ibaraki-ken 305, Japan

Date Visited: December 10, 1992

Report Author: D. Granville

ATTENDEES

JTEC:

D. Granville
V. Karbhari

HOSTS:

Dr. Takeshi Kitano	Director, Polymer Composites Laboratory
Dr. Takashi Tamaki	Sr. Officer for Research Planning

BACKGROUND

From 1993 onwards, a large group of laboratories at Tsukuba, including the Research Institute for Polymers and Textiles, will be divided into two major groups:

1. Biomaterials, with approximately 200 researchers
2. Materials (including plastics and composites), with 300-500 researchers

RESEARCH & DEVELOPMENT ACTIVITIES

Excellent Braiding Studies

Functional Gradient Materials

a. Controlling heat-resistance (fibers) and conductivity of materials
b. Controlling the distribution of fiber materials, in chopped mat form
c. Varying the polymer alloys used

d. Varying the fiber shape (profile)
e. Tension variability
f. Fiber orientation/control/gradient distribution
g. 2-D and 3-D braiding of composites with up to 3 reinforcements (3 attached articles by Dr. Kitano relate to this subject)
h. Water jets used to force short fiber reinforcement into mats so as to give through-thickness reinforcements

Chopped Strand Experiments

a. Effect of fiber length distribution before and after mixing/compounding
b. Influence on the number of filaments in chopped strand vs. mechanical properties

SUMMARY

The 3-D braiding machine was viewed in the lab, along with a number of braided prototypes. The possibilities of using the 3-D braider as a low-cost process to produce truss structures and cores for composite structures was discussed.

Site: **Mizuno Corporation**
R&D Department, Product Development Div.
12-35, 1-chome, Nanko-kita
Suminoe-ku, Osaka, Japan

Date Visited: December 9, 1992

Report Author: B. Kramer

ATTENDEES

JTEC:

J. DeVault
V. Karbhari
B. Kramer
D. Wilkins

HOSTS:

Mr. Kazuhiro Ohmori	R&D Dept, Product Development Division
Mr. Toshihiro Inubushi	Manager, Eng. & Development Dept., Product Development Div.
Mr. Takeshi Naruo	Section Chief, R&D Dept., Product Development Division
Mr. Takashi Ito	Deputy Mgr., Product Engineering Development Section
Mr. Rick Tsuruoka	Manager, International Marketing
Ms. Chikako Kamimukai	R&D Div., Product Development Div.

BACKGROUND

Mizuno, founded in 1906, is a leading manufacturer of general sports equipment. They manufacture all of their sports equipment internally. The JTEC team had discussions in the new headquarters building, but did not visit the production facility.

The discussions at Mizuno were largely limited to a question and answer period.

SUMMARY

Concerning golf shafts, U.S. shafts are 10% carbon fiber, while Japanese shafts are 50% carbon fiber. Mizuno produces golf shafts by sheet rolling. They use graphite in skis, tennis rackets, baseball bats, and sports shoes. They use 20 different kinds of carbon fiber, both PAN and pitch types. They have used graphite springs in shoes for five years and usage is not growing. They are not producing carbon-fiber bicycle frames now, but may be developing them. When asked why they decide to use composites in a given product, they indicated that it is very strong when compared to wood or steel.

Mizuno compression molds skis and blow molds graphite baseball bats (they consider themselves to be the leader) and tennis rackets with an expanding rubber bladder. They use computer analysis extensively, particularly for skis and golf shafts. Manufacturing is highly automated, with both robots and in-process sensing. Total waste amounts to only 2-3% of the composite sheet.

Mizuno considers SRIM (structural reaction injection molding) for tennis rackets to be a key technology for the future because it is a non-solvent process, and is completely automated and repeatable. They claim 60% by weight fiber content in SRIM and indicated that cross-linked polyesterimide is the best SRIM resin. All of their professional tennis rackets (20% of total production of 100,000 per year) are SRIM; the remainder are blow-molded.

Mizuno uses all kinds of hybrid fibers, preformed by braiding. Their process development emphasized steady improvement, rather than breakthroughs. They pick new products by looking for applications where high performance composites give real benefits. For example, large head tennis rackets cannot be fabricated from wood or metal because of their relatively lower stiffness.

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Site: **National Aerospace Laboratory (NAL)**
6-13-1 Ohsawa
Mitaka, Tokyo 181, Japan

Date Visited: December 7, 1992

Report Author: F. Xavier Spiegel

ATTENDEES

JTEC:

M. Ashizawa
D. Granville
V. Karbhari
B. Kramer
F. Spiegel

HOSTS:

Dr. Takashi Ishikawa	Section Head, Composite Structure Section, Airframe Division
Mr. Yasuo Tada	Director, Airframe Division

BACKGROUND

The National Aerospace Laboratories (NAL) has four divisions concerned with composites. NAL is not involved in manufacturing or fabrication but emphasizes testing with three divisions involved with mechanical testing. NAL's total 1991 budget was $85.5 million and they employed 439 people. Its capital investments in test and non-destructive testing (NDT) equipment were very impressive.

Dr. Ishikawa was full of enthusiasm and was quite proud of a CF/thermoplastic wing box model which was fusion bonded; he continued his enthusiasm as he discussed the characterization of CF/polyimide (in support of NASDA's Hope Project), testing machines with environmental chambers (up to 9 m x 5 m x 3 m), high temperature composites of SiC - SiC, tailoring of composites for space with zero coefficient of thermal expansion, a bi-axial testing machine (1 m x 1 m capacity with fully programmable load actuators), impact test systems, a thermal conductivity analyzer, and a mainframe and submainframe testing system. Their NDE efforts include an ultrasonic scanning system (robotic) using pulse-echo and back scatter (10 Mhz to 50 Mhz), thermal imaging, acoustic-emission, x-ray, and CT scanner.

The priority areas of research are chosen by NAL, not the fabricators. There is a thorough understanding of the problems of the fabricators and there are many domestic conferences for interaction. NAL pays for co-operative research and does the testing for all of its fabricators. There is a consistent budget and the manufacturers of the materials are funded for long-term research, typically 10-15 years. They are very patient and understand that failures will occur in research.

The tour of the facility was very impressive. The JTEC team saw many systems including thermal imaging, impact, a large environmental chamber, fracture toughness, ultrasonic imaging enhancement, and the random loading platform. The random loading platform was testing a C/PIX tape wound tubular main spar (see Fig. 4 in Ishikawa et al. 1991b).

SUMMARY

Dr. Ishikawa considers manufacturing costs as the main barrier to the use of composites. He anticipates advancements in high temperature resins and thermoplastics. Research on fibers must be conducted to reduce their cost rather than improve their quality. Improvements must be made in RTM tooling, preforms, and most importantly, resins.

There are many specialty weavers in Japan. NAL rates Toray as the best pre-preg manufacturer, Mitsui the best at high-temperature and tough resins, and Shikibo the best at fabric manufacture. Dr. Ishikawa is not satisfied with the quality of the pre-preg.

The carbon fiber market in Japan has not been significantly impacted by the slowdown in Japan's defense spending.

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National Aerospace Laboratory, Science and Technology Agency. 1992-1993. "Composite Structure Testing Facilities" (brochure). Tokyo.

Site:	**Nippon Steel Corporation** **Advanced Materials & Technology Research Laboratories** **Technical Development Bureau** **1618 IDA, Nakaharu-ku, Kawasaki 211** **Japan**
Date Visited:	December 6, 1992
Report Author:	V. Karbhari

ATTENDEES

JTEC:

V. Karbhari
D. Wilkins

HOSTS:

Dr. Kenji Kubomura	Chief Researcher
Hironori Maikuma	Senior Researcher

BACKGROUND

Nippon Steel is the world's largest producer of crude steel with production figures of 28.6 million tons in 1991. However, they have been aggressively pursuing the advanced composites market for a while with the long term goal of being the leaders in materials that would replace steel. Research is conducted through the Technical Development Bureau, which consists of six divisions, one of which, the Advanced Materials and Technology Research Laboratories, deals with composites. Corporate R&D controls funding of resources and personnel. However, only 40% of the budget is decided by this group, the remaining 60% being based on specific recommendations from business groups. This makes their research activities very applied in nature. There are 35-40 researchers working on PMCs under Kubomura and 25-30 more working in the area of polymer processing.

RESEARCH & DEVELOPMENT ACTIVITIES

1. Joint development projects with the automotive industry
   - o Carbon fiber reinforced drive shafts, centrifuges, and body panels
   - o Activities in fabrication, process development, materials characterization

2. Filament winding
   - o Large cylinders of 1" thickness
   - o Research to look at issues related to cracking
   - o Mostly done through experimentation since there was insufficient time for the use of models, although they did attempt to use Springer's model. Used sensors and controls in experimentation.

3. Honeycomb type prepreg
   - o Developmental project for inspection and quality control (QC)

4. Effect of holes and bolted joints in composites using pitch based carbon fibers
   - o Characterization and analysis
   - o This has been a major area of research in the recent past with special emphasis placed on the comparison of behavior and design of bolted joints in pitch carbon reinforced composites.

5. Use of Carbon fibers in construction
   - o Use of chopped fiber and continuous fiber for increased ductility and toughness
   - o Small scale models tested in bending
   - o Use of filaments in precast blocks
   - o Applications in precast and modular structures, including for prestressed concrete
   - o Reinforcement of caissons to be used for initiation of bores (C is easier to cut through than steel). This is marketed as a novel material shield-cuttable tunnel wall system (NOMST) and has been used for tunnels in Japan.
   - o Developmental work on use of glass for the Japan-France monument

   (This seems to be a major applications area)

6. Surface Treatment
   - o Use of oxidizing layers on fibers for interfacial strength augmentation

7. Hybrid composites
   - o Investigation of layered pitch/PAN based laminated structures

SUMMARY

Nippon Steel uses filament winding, autoclave cure, stamping of thermoplastic sheets, and is developing a modification of RTM for high fiber volume structures. Their main target areas for the use of composites are in the automotive, construction

and engineering machinery sectors. Although recycling is an issue, they do not believe that it will kill the thermoset market. Cost, quality control and speed of fabrication are still major issues.

They viewed MITI led projects to be useful as catalysts for the extended internal funding of projects.

Marketing, even of R&D activities, is done through the presentation of generic research to potential customers. The customers are then allowed to come up with applications for the materials systems and processing techniques. This then leads to the establishment of a joint research project or a developmental project at Nippon Steel.

Projects in construction applications and in the transportation sector are viewed as having potential for future growth.

The key to the initiation of projects was a full blown cost analysis, which presupposed success.

Site: **Shimizu Corporation**
Seavans South
No. 2-3, Shibaura 1-chome,
Minato-ku,
Tokyo 105-07, Japan

Date Visited: December 11, 1992

Report Author: D. Granville

ATTENDEES

JTEC:

D. Granville
V. Karbhari
J. McDermott
X. Spiegel
D. Wilkins

HOSTS:

Dr. Toshiaki Fujimori	Deputy Director, Technology Div. Executive V.P., S. Technology
Mr. Minoru Sugita	General Manager, Technology Div.
Mr. Takatoshi Ueno	Manager, Planning Dept., Technology Div.
Mr. Kenichi Sekine	Manager, Sales Dept., NEFCOM Corp.
Mr. Mohi U. Ahmed	Planning Dept., Technology Div.

BACKGROUND

Shimizu Corp., one of the largest architect/engineering/construction firms in Japan, is the leader in the application of composites in the construction industry. Shimizu was founded in 1804 and provides architecture, property development (living and working environments), engineering, and construction. They employ 4,500 architects and engineers. Examples of their accomplishments include the New Tokyo Metropolitan Building complex, Kansai International Airport, dams, Tokyo Gas Works, Kashiwazaki Nuclear Power Plant, and the Great American Plaza and Resort Hotels.

In 1987, Shimizu established a space construction office for NASA. This endeavor will include concept design and construction materials. They are considering circular dams for the ocean and desert living sites.

Shimizu's composite construction products include "NEFMAC," a reinforcement for concrete (carbon, glass and aramid formed as an integrated mesh), which is resistant to the chemicals in concrete and therefore corrosion. This system is dependent on the mechanical interfacing of the grid to the concrete, but can reduce the volume of concrete required for strength. NEFMAC is non-magnetic but is most importantly, light weight. It can be layed in and held using air-powered staple guns. Although the cost is three to five times that of re-bar, it requires one-third the labor cost, has lower transportation and lower maintenance costs.

"NESTEM," an FRP geogrid, is produced for road reinforcement and stabilization as well as embankments, retainments and foundations (especially useful in arctic regions because its low weight transportation costs are drastically reduced). It also has many marine applications, e.g., for oil platforms, underwater structures, and pontoons.

RESEARCH & DEVELOPMENT ACTIVITIES

Shimizu is engaged in R&D efforts in a wide variety of fields, including materials research ranging from underground to space construction applications, intelligent buildings, and more. See the JTEC report on construction technology in Japan (1991) for further information. Activities described below and elsewhere in this report relate only to applications of polymer composites.

NEFMAC and NESTEM grids have specifications for graphite and Kevlar. Both use continuous forming. Batch forming can be accomplished by manual layup for any size grid.

Shimizu is forming design committees for building construction to develop "Design Codes" by setting up a consortium with goals and newly updated property tests. R&D activities include FEA structural analyses using computer controlled structural member testing for new construction materials, modeling and simulation codes. The development of vibration damping/dissipation composites of multi-layered rubber and then metal plates in building foundation is being pursued.

SUMMARY

Discussions during the JTEC team's visit included the Shimizu suppliers (Asahi, Toray, and Nippon Steel) and new market opportunities. Shimizu's current market for NEFMAC is about $2 million/year.

New opportunities include the development of automated materials handling and dispensing equipment for fabricating, transporting, and installing NEFMAC and NESTEM composite grids for underground tunnels, storage tanks, building walls, etc.

REFERENCES

Shimizu Corporation. 1992. "R&D Research and Development" (brochure).

Shimizu annual report and corporate data till March 31, 1992.

Site:	**Toray Industries, Inc.** **Ehime Plant** **1515 Tsutsui, Masaki-cho** **Iyogun, Ehime 791-31, Japan**
Date Visited:	December 12, 1992
Report Author:	F. Xavier Spiegel

ATTENDEES

JTEC:

J. DeVault
D. Granville
J. McDermott
F. Spiegel
D. Wilkins

HOSTS:

Mr. Akira Takeo	Assistant General Manager, ACM Technology Dept., Head Office
Mr. Hiroshi Ohnishi	Manager, LSS Development Dept., Technology Center, Ehime Plant
Mr. Hideo Komatsu	Dir., General Manager Large Scale Structure Project & Composite Materials Research Labs, Ehime Plant
Mr. Hiroyoshi Tanaka	Deputy General Manager, Composite Materials Research Labs, Ehime Plant
Mr. Koji Kozuka	Manager, Composite Fabrication Dept., Advanced Composite Materials Div., Shiga Plant
Mr. Minoru Kitanaka	General Manager, LSS Development Dept. Technology Ctr., Ehime Plant
Mr. Nobuyuki Odagiri	Sr. Research Chemist, Composite Materials Research Labs, Ehime Plant

BACKGROUND

Toray is the number one Japanese company in quality and quantity for the manufacture of carbon fiber. Ten percent of Toray's composites business is structures.

Toray's composite related organization is composed of the following four divisions:

Composite Materials
Manufacturing
Research and Development
Technical Center and Administration

The Manufacturing Division is composed of the Shiga Plant (composites) and the Ehime Plant (carbon fiber, prepreg). The Research and Development Division contains the Composite Materials Laboratories. The Composites Materials Division is composed of carbon fiber, carbon sports goods, composite materials, ACM technology, and the administrative departments. The technical center contains the Large Scale Structures Project Group. Net sales (April 1, 1990 - March 31, 1991) were $6.5 billion, with the following distribution:

Synthetic Fibers	48.4%
Plastics and Chemicals	26.3%
Housing & Engineering	15.8%
New Products & other[1]	9.5%

The Toray Group (domestic and overseas subsidiaries and affiliated companies) includes 119 domestic and 58 overseas companies. The parent company has 10,116 employees, the domestic subsidiaries have 8,393, and the overseas subsidiaries have 7,502. Toray forecasts the worldwide pan-based carbon fiber capacity to be 11,505 tons/year. Worldwide consumption in 1991 was estimated at 6,170 tons. Toray forecast pitch based carbon fiber capacity to be 2,054 tons/year in Japan. Toray's approach to business is the market/demand system. They enter a market where management expertise is available, where there is a market demand, and where the host government or industry requests their expertise. The Toray Group was the first company to qualify carbon/epoxy for the Boeing 777.

In 1991, they announced APG 2000, their long-term corporate vision, which sets out the Group's aims by the year 2000. The "G" in the name denotes the three concepts that guide their business strategies: Growth, Group Management, and Globalization.

RESEARCH & DEVELOPMENT ACTIVITIES

Although Toray's R&D activities are numerous, emphasis is placed on automatic filament winding, pultrusion, and resin transfer molding.

[1] New products and other business activities are listed by Toray as: carbon fiber, reverse osmosis membranes, printing plates, plastic glasses, artificial kidneys and pharmaceuticals.

Toray is determined to develop a structures business.

Its major efforts in resin development are aimed at toughened PI and BMI resins. However, not much work is being done on thermoplastic resins. In RTM, they believe that the main challenge lies in the preform rather than the resin.

Currently, automotive efforts in Japan appear to be limited to drive shafts only.

They answered a set of questions sent by the panel, which are attached for reference.

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Site: **Toyota Motor Corp.**
Higashifuji Technical Center
1200, Mishuku, Susono
Shizuoka 410-11, Japan

Date Visited: December 8, 1992

Report Author: D. Granville

ATTENDEES

JTEC:

D. Granville
V. Karbhari
J. McDermott

HOSTS:

Dr. Masatoshi Matsuda	Project Manager, R&D Development Div. II
Mr. Yoshiki Murashima	Project Manager, R&D Planning Div.

BACKGROUND

This plant makes SMC rear covers for the MR-2 engine and side air housings, sun roof housings, and spoilers with SMC molding (1500-2000 ton machines).

RESEARCH & DEVELOPMENT ACTIVITIES

They are evaluating carbon/epoxy drive shafts made by GKN (French company) on the MARK II (Cressida) in Japan.

They are evaluating RTM for structural body parts and SMC for exterior body parts.

Recent research has been conducted on batteries for electric cars, on leaf springs, and suspension components. Toyota has evaluated composite wheels but found them to be unreliable.

Other activities include LCPs, surface glazing materials (high abrasive resistance), and new TPs with high modulus.

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Toyota Motor Corporation. 1989. "Toyota Higashi Fuji Technical Center" (pamphlet).

"Sun God or UFO," *Plastics News* 4 (38).

Site: **Nikkiso Co., Ltd.**
43-2, Ebisu 3-chome, Shibuya-ku,
Tokyo 150-91, Japan

Date Visited: December 9, 1992

Report Author: D. Granville

ATTENDEES

JTEC:

M. Ashizawa
D. Granville
J. McDermott

HOSTS:

Mr. Masahiko Hatano	Pres. & Chief Operating Officer [now Vice Chmn.]
Mr. Toshiaki Noda	General Manager, Central Research Ctr.[2], Licensed Technical Translator
Mr. Takashi Ohsaki	Leader, Central Research Center
Dr. Kazuo Miyamichi	Central Research Center
Mr. Shinya Asada	Manager, Engineering Dept., Advanced Materials Factory, Shizuoka Plant
Mr. Fumio Kida	Manager, Advanced Materials Factory
Mr. Kohichi Imai	Chief Staff, Central Research Ctr.

BACKGROUND

Mr. Masahiko Hatano, President of Nikkiso Co., Ltd. at the time of the JTEC team's visit (now Vice Chairman), used to work at Toho Beslon Co., Ltd. as a vice president in charge of establishing a carbon fiber (CF) manufacturing technique.

Mr. Hatano has now succeeded in the commercialization of some of the major constituent components of airplanes utilizing CFRP, and also in the development of a brand new production technique of graphite whisker. Nikkiso continues to grant its CF production technique by licensing.

[2] As of Dec. '93, the Central Research Center was renamed the "R&D Center"

RESEARCH & DEVELOPMENT ACTIVITIES

Nikkiso has an advanced materials factory to develop and produce high quality complicated composite parts for the aerospace and industrial markets, such as thrust reverser cascades (in production), precooler inlet scoop (BMI, FAA certified), a fairing track for thrust reversers (with epoxy), unmanned helicopter frames, steering wheels, and racing motor frames. They have developed their own automated layup machine and RTM technology, and have filament winder, autoclave, hot press, and water jet cutter. Full characterization, NDE (super soft x-ray) design and analysis, and FEA are done in-house.

Special features of the carbon fiber manufacturing process (licensed to the Boeing Company and Tae Kwang Industrial Co., Ltd.) include comonomers with a suitable oxidation speed, continuous solution polymerization (high molecular weight and its narrow distribution), incorporating a salt solution for spinnability, dry/wet spinning at high speeds, oiling agent for lubricating to separate filaments, and high-stretch carbonization for high strength.

Nikkiso has developed a low cost but high quality graphite whisker (GRASKER) for commodity applications including friction and wear materials, electroconductive materials, and battery electrodes.

Nikkiso has recently developed continuous fiber-reinforced ceramic composites (CFCC) for high temperature application.

SUMMARY

If the cost of carbon fiber were reduced to less than $10/kg., then it is believed that greater commodity use of carbon fibers and pre-pregs would occur despite the assembly and fabrication costs. They are working with major battery makers to develop high energy storage batteries using GRASKER anodes, as well as electroconductive inks for flexible circuit boards and TPs/TSs for wear resistance materials.

REFERENCES

Nikkiso Company, Ltd. "Nikkiso Outline & Products," 1992 annual report.

------. "GRASKER," at Nikkiso Shizuoka Plant, December 9, 1992 (viewgraphs)

------. Technical Information, "GRASKER Graphite Whiskers" No. 1.

Site: **University of Tokyo**
7-3-1 Hongo
Bunkyo-ku 113, Japan

Date Visited: December 7, 1992

Report Author: F. Xavier Spiegel

ATTENDEES

JTEC:

M. Ashizawa
D. Gill
V. Karbhari
B. Kramer
F. Spiegel

HOSTS:

Dr. Isao Kimpara	Professor, Dept. of Naval Architecture and Ocean Engineering
Mato Heder, M.Sc., Ph.D.	Dept. of Naval Architecture and Ocean Engineering

BACKGROUND

The Kimpara-Kageyama Laboratory in the Department of Naval Architecture and Ocean Engineering is concerned primarily with the characterization of the mechanical properties of graphite and Kevlar composites. Their testing is performed on coupons supplied by industry; they do little fabrication of their own.

Non-destructive evaluation is emphasized. Delamination is studied using C-scan and acoustic emission. Vibration pattern images are also used for damage evaluation, and some fatigue testing is conducted.

Dr. Kimpara believes the trends in composites are identical in Japan and the United States. He sees future new applications in civil engineering (especially concrete structure repair), and in transportation, if costs can be reduced. In manufacturing technology Dr. Kimpara considers production improvements are needed in resin transfer molding, vacuum bag molding, and room temperature curing. He considers Aramid fiber use other than in the aerospace industry to be crucial. The main

problems in naval use of composites lie in the damage tolerance of composites to impact.

Dr. Kimpara noted the difference in the educational systems of Japan and the U.S., mentioning that the universities of Japan are quite independent. Coordination is not unified. Their funding is from the Ministry of Education, not MITI.

The visit concluded with a brief tour of the Kimpara-Kageyama Laboratory where the JTEC team met Dr. Mato Heder. The equipment was typical of a small university laboratory -- modest but adequate. The research at this facility is primarily in the area of mechanical testing.

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Site:	**Yamaha Motor Co., Ltd.** **2500 Shingai, Iwata, Shizuoka 438** **Japan**
Date Visited:	December 8, 1992
Report Author:	D. Granville

ATTENDEES

JTEC:

D. Granville
V. Karbhari
J. McDermott

HOSTS:

Mr. Kohtaro Horiuchi	Dir., Sr. General Manager, Marine Div.
Mr. Akira Kubota	Manager, Eng. Div., Marine Operations
Mr. Hisao Aono	Manager, Production Dept., Marine Operations
Mr. Takashi Motoyama	Assistant Manager, Horiuchi Lab
Mr. Osamu Hashimoto	Chief Engineer, Production Eng.Dept., Marine Operations
Mr. Masao Yokouchi	Assistant Manager, Production Eng.Dept., Marine Group

BACKGROUND

Yamaha developed human-powered and solar-powered racing boats for competition along with an America's Cup racing boat. The construction of the America's Cup boat is urethane paint, unidirectional carbon fibers/epoxy pre-preg and honeycomb core. They use low temperature cure pre-preg and vacuum bag molding methods on plywood tools. On the other hand, the construction of ocean-going boats is unidirectional T-glass epoxy, Kevlar woven cloth, and PVC foam. They use room temperature cure and vacuum bag molding methods, with reinforcement fibers laid up and impregnated by hand with resin on plywood tools. A new product is a remote-controlled agricultural helicopter sprayer.

Yamaha began working with composites in 1960 (boats). Yamaha instructs suppliers to satisfy resin/feedstock quality as specified by its engineers, and inspects these materials when received. It also has its own educational program that includes

apprenticeship education and training in manufacturing methods, rendered by senior and junior engineers. Yamaha specializes in "one-off" custom designed boats and low-rate production boats. There is no automated equipment except for chopper gun and gel coat paint spraying equipment. They use glass fiber reinforced plastics mold for production boats and plywood tools for trials and "one-off" custom designed boats.

RESEARCH & DEVELOPMENT ACTIVITIES

America's Cup yacht -- use of low temperature pre-preg in sandwich/skin construction on plywood tools with vacuum bags. Designed using "rule-based" design guide based on consensus hydrodynamic design by a technical committee composed of design experts from universities and industrial partners. Then "building simulation" is completed by fabricating sub-scale components and finite element materials (FEM) study and panel tests (small and large). Their NDE testing procedure is not fully developed.

Racing sculls are composed of two-ply graphite uni-tape, "Klegecell" foam and two-ply graphite uni-tape, fabricated manually. Their solar-powered one-man racing boat and human-powered racing boat are also fabricated manually.

They are currently marketing a radio-controlled helicopter for agricultural spraying applications called the R-50. The helicopter has a fuselage of 2655 mm, with a main rotor of 3070 mm diameter, and a 98 cc engine. The blades and body enclosure are fiberglass and layed-up by hand. Weight is 67 kg.

SUMMARY

"Hobby-shop" type activity was displayed during the tour of the Yamaha plant. This is a factory for trials and "one-off" custom designed boats only. They have six factories for production of boats located throughout Japan (Shizuoka and other prefectures). When asked if this facility is also used to build custom or prototype composite parts/assemblies for Yamaha's other activities (motorcycle shrouds/enclosures) the answer was yes, but to a limited extent. This division mainly makes trials and "one-off" custom-designed boats where automation has no advantage since each boat is unique or made in small quantity. They make it a rule to have discussions with suppliers of composite feedstocks and resins beforehand, so that they can receive materials that have been altered according to specifications. Other than thermocouples, no processing feedback monitoring/control was observed, and they had only visual NDE capability. Yamaha's greatest cooperative effort is extensive design and modeling with Japan's technical universities and

industry in support of the America's Cup effort. Yamaha uses a push-pull system for styrene emissions.

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APPENDIX D. QUESTIONNAIRE FOR JAPANESE COMPANIES

The JTEC team prepared written questions to be asked of the Japanese hosts during its site visits. The questions ranged from the general to the specific.

1. Do you have a company brochure? If you do, please provide it to us. If not, please give us a brief presentation on your company: history, size, facilities, products, sales, future growth and other pertinent information.

2. Do you have a brochure or presentation material on composite products and activities at your company? If you do, please provide it to us, and also give us a brief oral presentation on them.

3. Please provide us with a list of your company's composite manufacturing related facilities and equipment. Does your company own any unique facility or equipment? Who provided or designated this unique facility or equipment?

4. How do you rate your company's composites facilities and equipment relative to other Japanese companies? American companies?

5. What would the cost of prepregs be for the widespread application to industry? Do you think the material suppliers can meet the desired cost soon?

6. We believe JTEC has already sent you a list of manufacturing technologies (hand layup, filament winding, pultrusion, etc.) and related items (curing methods, tooling concepts, quality assurance, CAD/CAM, etc.). Which of those does your company use? And which of those does your company not use and why?

7. Is there any other manufacturing technology and related items which your company is using or had used but was not specified on the list provided by JTEC? If yes, please tell us. Was it successful? Was it a failure? Why?

8. Please tell us more in detail on those manufacturing technologies and related items which your company uses frequently. Why does your company use them frequently -- for cost, good quality, customer request, or what?

9. If your company is asked by a major customer to bring your company's favorite or most successful manufacturing technologies and related items, what would your company bring?

10. If your company is asked to bring only "one" manufacturing technology, which one does your company bring? And why? Do you think the selected manufacturing technology is the best in Japan? If not, who has the best in Japan? Do you think it is better than the one in the U.S.?

11. The composite industry expanded at an impressive rate of more than 17% per year, but recently it really slowed down (flat to negative expansion). Is there any future for the composite industry? What do you think are the cause(s) of the slowdown? Has your company (and also other companies in Japan) been affected by the slowdown?

12. How much of the slowdown is affected by the general economic slowdown? How much is affected by the "high cost" of composites components relative to metal components? How much is affected by the lack of or inefficient manufacturing technology?

13. The general economic slowdown aside, the major cause of the slowdown in the composite industry is said to be the "high cost of composites." What are the steps your company is taking to lower the cost? Please be specific.

14. Nowadays we are hearing often that the reduction in cost of composites will come from improved or innovative manufacturing technologies. Which manufacturing technologies do you think will lead to a breakthrough in cost reduction? And why?

15. Which manufacturing technologies and related items will be the focus of your company's attention and future R&D investments? And why?

16. To reduce the cost of composite components in the future, the following manufacturing technologies are currently under study in the United States: stitched RTM; tow placement; 3-D (textile) weaving; pultrusion; forming/stamping/molding/rolling for thermoplastics. Is your company working on any one of these technologies? Which? And how intensively?

17. What are the prospects for these technologies? What are the major problems associated with the current manufacturing technologies?

18. Is there any other promising manufacturing technology under study at your company? If so, please tell us about it.

19. For improving manufacturing cost, where does your company put priority? On equipment? On facility? On personnel? or on other things?

20. What manufacturing technology breakthrough is required for a major cost reduction which will lead to a widespread use of composites? Besides manufacturing technology, what other things are necessary for a widespread use of composites as we have with metals (steel and aluminum)? What are the hurdles? What should be done to remove the hurdles?

21. In which manufacturing technologies does Japan excel relative to other countries? Which manufacturing technologies do you think the U.S. excels in relative to other countries? What do you think about European manufacturing technology?

22. Would your company think about cooperative R&D efforts with American companies? What manufacturing technologies do you think an American company should or can learn from the Japanese companies? and vice versa?

23. Our questions so far were mainly concentrated on manufacturing technologies; but to reduce overall cost of composite components for aerospace usage, other areas are also critical. Please tell us what you are doing in other areas. For example, engineering, quality assurance, procurement, certification, training, morale, and other areas.

24. Where do you expect the composite technology and business to be in 1995, 2000, 2010? What is your company's plan to cope with coming changes and progress?

25. Are you cooperating with other Japanese companies in composites? Through engineering associations? Which ones?

26. Do you think cooperation between Japan and U.S. will help accelerate the widespread use of composites? Would you be interested in continuing communication on manufacturing technology? Is there a focus for this communication in Japan? Where?

27. In your company's opinion, what is the single most important thing for success? Is it manufacturing technology? capital? people? company tradition? experience? technology? facility? location? Or what is it?

28. To your company, what is the definition of an excellent company? How about a successful company?

29. Can you add anything more to our questions or to your answers?

APPENDIX E. GLOSSARY

ACEE	Aircraft Energy Efficiency program
ACM	Automated Composite Material; Advanced Composite Material; Automatic Cutting Machine
ACT	Advanced Composites Technology
AE	Acoustic Emission
AI	Artificial Intelligence
AIS	Accounting Information System
ANSI	American National Standards Institute
APC	Automatic Ply Cutting Machine
Aramid	An organic fiber such as Kevlar$_{TM}$ or Technora$_{TM}$
ASTM	American Society for Testing and Materials
ATF	Advanced Tactical Fighter
ATL	Automated Tape Layup
Autoclave	A primary production curing vessel
BMI resins	Bismaleimide resins
Broadgoods	Wide fabrics (usually on a roll)
CAD	Computer-Aided Design
CAI	Computer-Aided Inspection; Compression-After Impact
CAM	Computer-Aided Manufacturing
CATIA	Proprietary Computer-aided design program from Dassault (French Company)
CAV project	Composite Armored Vehicle
CERC	Concurrent Engineering Research Center (U.S.A.)
CF	Carbon Fiber
CFCC	Continuous Fiber-Reinforced Ceramic Composite
CFRP	Carbon-Fiber Reinforced Plastic
CIM	Computer-Integrated Manufacturing
CMCs	Ceramic-Matrix Composites
CNG	Compressed National Gas
CRAD parts	Contract Research and Development parts
CTE	Coefficient of Thermal Expansion
CVD	Chemical Vapor Deposition
Delamination	Debonding of laminate
DSC	Differential Scanning Calorimetry
DOC	Direct Operating Cost

DoD	Dept. of Defense
DSS	Decision Support System
FEA modeling	Finite Element Analysis Modeling
FEM	Finite Element Methods
FRP	Fiber-Reinforced Plastic
GFRP	Glass-Fiber Reinforced Plastic
GRASKER	Graphite whisker
HSCT	High Speed Civil Transport
IPD	Integrated Product Development
IRADs	Independent Research and Development (projects)
ISO	International Standards Organization
JDA	Japan Defense Agency
JSAMPE	Japan Society for the Advancement of Materials and Process Engineering
JSCM	Japan Society for Composite Materials
Keiretsu	Loose associations of Japanese businesses characterized by reciprocal stock ownership and long-term supplier/customer relationships
Kitting	Gathering sub-elements into a "kit" for assembly
Layup	Stack of composite lamina
LCPs	Liquid Crystal Polymers
LDF	Long Discontinuous Fiber (Trademark of DuPont)
Material Transformation Process	Set of activities that transfer a given set of raw materials into a final stage
Mechatronics	Study of electro-mechanical devices
Micromechanics	Mechanics of fiber-resin interactions
MITI	Ministry of International Trade & Industry (Japan)
MMC	Metal-Matrix Composite

NAL	National Aerospace Laboratories (Japan)
NDI	Non-Destructive Inspection
NDE	Non-Destructive Evaluation
NEFMAC	New Fiber Composite Material for Advanced Concrete A Shimizu composite construction product which is light weight and non-magnetic, a reinforcement for concrete (carbon, glass and aramid formed as an integrated mesh)
NESTEM	An FRP Geogrid produced for road reinforcement and stabilization a continuous production operation
NIST	National Institute of Standards and Technology
NOMST	Novel material shield-cuttable tunnel wall system
PEEK	PolyEtherEtherKetone
Photochromatic	The ability to darken in bright light but revert to original color when source of light is removed
PI resins	Polyimide resins
Pin-winding	Method of production used to produce NEFMAC
Ply	Layer of composite (Lamina)
PMC	Polymer-Matrix Composite
PRP	Product Realization Process
Pultrusion	A continuous composite fabrication technique
QA	Quality Assurance
QC	Quality Control
QFD	Quality Function Deployment
Resin	A polymer used to bind fiber
RIM	Reaction-Injection Molding
RIPT	Research Institute of Polymers & Textiles (Japan)
RTM	Resin Transfer Molding
SACMA	Suppliers of Advanced Composite Materials Association
Shotcrete	Method of applying concrete with high-pressure air
SMC	Sheet Molding Compounds
SPC	Statistical Process Control
SRIM	Structural Reaction Injection Molding
Stochastic process	A process that has some element of probability in its structure

TDB	Technical Development Bureau
TP	Thermoplastic
Tow placement	Combination of filament winding and tape laying technology
TQD	Total Quality Design
TQM	Total Quality Management
TS	Thermoset
USAF	U.S. Air Force
Whisker	Short, stiff fiber

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